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State of the Art Report

THREE-DIMENSIONAL DISPLAYS: PERCEPTION, IMPLEMENTATION, APPLICATIONS

Christopher D. Wickens
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University of Illinois
October, 1989

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			

4. PERFORMING ORGANIZATION REPORT NUMBER(S) CSERIAC-SOAR-89-001		5. MONITORING ORGANIZATION REPORT NUMBER(S) AAMRL-TR-90	

6a. NAME OF PERFORMING ORGANIZATION University of Dayton Research Institute	6b. OFFICE SYMBOL (If applicable) AAMRL/HE/CSERIAC	7a. NAME OF MONITORING ORGANIZATION AAMRL/HEX

6c. ADDRESS (City, State, and ZIP Code) 300 College Park Dayton, Ohio 45469-0001	7b. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB, OH 45433-6573

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Armstrong Aerospace Medical Research Laboratory	9b. OFFICE SYMBOL (If applicable) AAMRL/HEX	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DLA900-87-R-2498

8c. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB, OH 45433-6573	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO. 62202F	PROJECT NO 7184	TASK NO 12	WORK UNIT ACCESSION NO. 22

11. TITLE (Include Security Classification)

Three-Dimensional Displays: Perception, implementation, and Application

12. PERSONAL AUTHOR(S) C. D. Wickens, S. Todd, and K. Seidler

13a. TYPE OF REPORT Technical	13b. TIME COVERED FROM 1-89 TO 10-89	14. DATE OF REPORT (Year, Month, Day) October 1989	15. PAGE COUNT 126

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Displays, Three-Dimensional(3-D) Displays, Predictive Displays, Graphics, Aircraft, Air Traffic Control, Meteorology, Tele-operation Vision, Visual Perception, Motion Perception
FIELD	GROUP	SUB-GROUP	
23	02		
01	04		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Reuben L. Hann	22b. TELEPHONE (Include Area Code) (513) 255-8821	22c. OFFICE SYMBOL AAMRL/HEX

DD Form 1473, JUN 86   Previous editions are obsolete   SECURITY CLASSIFICATION OF THIS PAGE

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October 1989

Accession For
NTIS CRA&I
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Justification

By Price $35.00 HC
Distribution/
Availability Codes
Avail and/or
Dist   Special
A-1   21

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ABSTRACT

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CSERIAC REPORT

1.0 INTRODUCTION

Emerging technology has created a number of new opportunities for display design. Two technological forces in particular have allowed the development of three-dimensional (3D) displays in a variety of crew station systems. Increases in the speed of computer graphics software and hardware, coupled with advances in dynamic stereoscopic imaging technology, have enabled the design of displays which, by more closely resembling the domain of objects and events they are meant to depict, provide more "natural" viewing conditions. This greater naturalism results from the direct coding of distances along the line of sight into the display, which is accomplished by using various aspects of display technology. We refer to this distance information as the "depth axis" or z-axis of a display. Our definition of the term "3D" encompasses the use of any technique, whether stereoscopy or any of the cues that artists build into a perspective painting, to create a sense of depth along the z-axis.

Examples of 3D display applications abound and will be described in considerable detail in later sections of this report. Representative examples can be drawn from the field of aviation: the pilot's map of the approach path or rendezvous point; the display of aircraft locations in the airspace used by air traffic controllers; displays of geographical and topographical features used by helicopter pilots. These 3D displays all serve to provide the viewer with a better understanding of physical location and situation awareness. Displays of this sort are beneficial outside aviation as well. The

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meteorologist can gain a better understanding of an evolving weather pattern by viewing a 3D representation of air patterns; operators of remotely manipulated vehicles, or teleoperator (remote manipulator) systems will benefit from the precise depth representation of the environment; human factors designers, using 3D displays along with the anthropometric model of a workspace, can better envision how the intended worker will function there, and the constraints the space will impose on movement. In the preceding examples, depth dimensions conveyed by display techniques generally correspond directly with depth or distance in the physical world. Such display techniques have also been used to represent nonspatial characteristics. One example might be the use of overlaid "windows" in computer systems like the Apple Macintosh. Here distance has ordinal, not metric properties, and is used to convey a sense of priority or recency. A common example is the use of the depth axis in 3D graphics to represent mathematical relationships involving 3 (or more) variables. Great strides in this area have been made recently in the field known as "scientific visualization," (McCormick et al., 1987) in which complex equations can be generated, and 3D graphics images rotated and "explored" in a way that allows a better appreciation of the relation between variables.

Two basic human factors arguments may be made for the implementation of 3D displays: (1) The visual scene of a 3D world is a more "natural," "ecological," or "compatible" representation than that provided by 2D displays; and, closely related, (2) A single integrated representation of one object, relation, or scene reduces the need for a mental integration of two or three representations.

Despite the intuitive appeal of the preceding arguments and the esthetic appeal of most 3D renderings, the advisability of implementing 3D displays is

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not a foregone conclusion. There are three potential costs or risks associated with this display technology.

(1) As Gregory (1977) has so eloquently argued, any representation of a 3D world on a 2D image surface produces an inherent ambiguity. The absolute distance represented by a point along the line of sight cannot be ascertained with high accuracy, compared to absolute distances parallel with the viewing image plane (the plane orthogonal to the line of sight). (This limitation is also characteristic of direct viewing.) Thus, 3D displays create the potential for perceptual ambiguity.

(2) Somewhat related to point 1, the integration of all 3 dimensions of space into a single 3-dimensional object may result in reduced precision in reading values along any one particular axis (Carswell & Wickens, 1987). Thus, the improved holistic awareness of space, gained by 3D representation, may be gained at the expense of analytic detail.

(3) 3D displays usually bring with them an added set of design issues, such as establishing the optimum field of view and viewing angle, along with technological hardware issues (related for example to glasses or image generation in stereoscopic displays), which considerably complicate the display designer's task. These issues will be discussed in Section 4 of this report.

The preceding suggests that the advantages gained by 3D technology are probably somewhat task specific and that tasks in which a holistic awareness is critical may be facilitated by the use of 3D technology. Whatever the task, it is true that the sense of depth we gain from a display depends upon a number of depth cues that can be incorporated to simulate a sense of "natural" 3D world viewing. In the following report, Section 2 describes the nature of those cues from the standpoint of basic human perception. Section 3 discusses

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how depth cues work in combination and, therefore, how the display designer can create the strongest sense of depth by choosing appropriate cues. Section 4 addresses some issues in going from the perceptual description of the cues to their actual display implementation. Section 5 presents a review of studies that have examined and evaluated 3D display technology in 6 main application areas: aviation, air traffic control, graphics, geosciences, computer-aided design, and medical imaging. It should be noted that much of the applied design research in Section 5 has not appeared in peer-reviewed scientific journals. Effort has been made by the present authors to establish the validity of those reports and proceedings papers included, which have not received this review.

2.0 BASIC CUES FOR DEPTH PERCEPTION

The designer of any 3D display seeks to create a compelling and accurate sense of three-dimensionality, signaling to the viewer such information as an object's relative and absolute distance, its 3D shape, and its orientation or the "slant" of its surfaces. In the current section we shall first describe a number of cues that the human perceptual system uses to extract this information from the visual scene, along with various constraints to their application. With appropriate display technology any and all of these cues can be incorporated into synthetic displays. Then in Section 3, we discuss empirical data from perceptual experiments that have examined the strength or salience of these cues in creating a compelling sense of depth. This is critical information for the display designer, who must weigh the advantages of more or better depth perception cues against the expense of the extra programming or more sophisticated (and therefore less reliable) technology necessary to provide them. Hence, the designer should have information regarding the most compelling cues.

The phenomenon of depth perception may be delineated into three parts: judgments of absolute distance, judgments of relative distance, and the perception of an object itself as three dimensional. A judgment of absolute distance is paraphrased as "How far away is that object from my point of view?"; relative distance as "How far apart are those objects from each other?"; and object perception as "What is the true 3D shape of that object?"

While the objective world consists of 3D objects with weight and volume, our visual perception of this world is built upon the two-dimensional images that fall upon our retinas. In order to transform these images into a perception with depth we utilize a number of "depth cues." These depth cues result from consistent patterns seen in the two-dimensional images that depict

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the 3D world and from the physical structure of the human visual system.
These depth cues may be represented in the objective stimulus present on the
retina or by the state of the visual system--its optics and its muscles. The
former are sometimes referred to as _pictorial_ or _world-centered_ cues. The
latter are referred to as _observer-centered_ cues.

Depth cues may be classified under the effects of light, occlusion,
object size, height in the visual field, the effects of movement, muscular
sensations, and binocular viewing. The following list of depth cues is
organized according to this categorization. Each cue description is followed,
where applicable, by a list of constraints that would limit the effectiveness
of the cue as it is incorporated into display design. Visual interpretation
of these cues in an aviation context can be facilitated by reference to Figure
2.1. Descriptions of Figure 2.1 in the text below refer by number to specific
cues in the figure.

2.1 Light

2.1.1 _Luminance/brightness_ effects. Objects, parts of objects, or
simply regions may be perceived to be at different depths as a result of
differences in luminance emanating from the various parts of the object (also
see 2.1.3, Shadows and highlights, below).

Egusa (1977, 1983) examined the perception of two adjacent regions when
the two regions were shaded with combinations of achromatic hues: black,
three shades of gray, and white. He found that as the brightness difference
between the regions increased, the amount of depth perceived separating the
regions increased. Unfortunately, the direction of this perception differed
between subjects. There was no consistent trend for the darker shades to
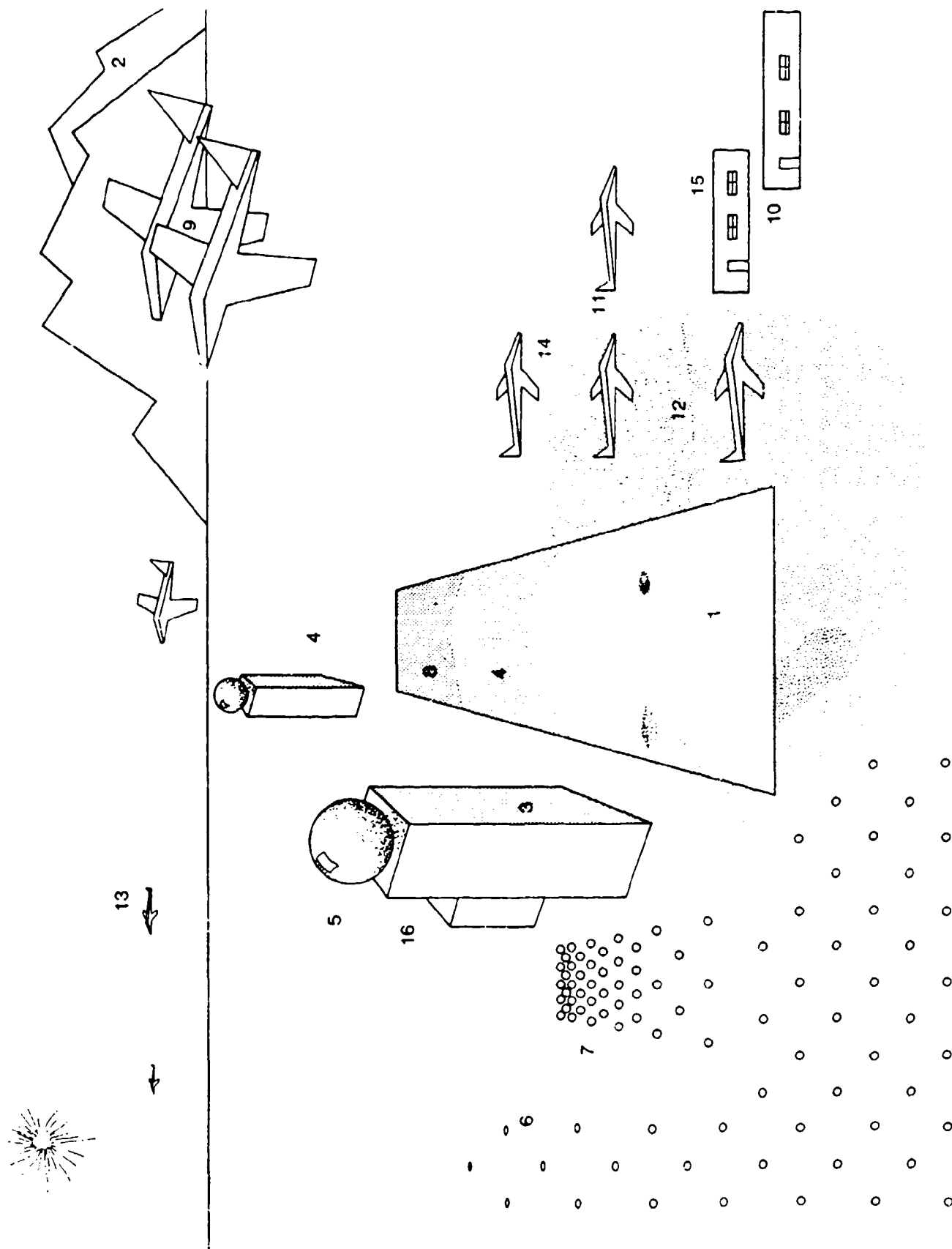signal either closer or more distant regions.

Figure 2.1. An example illustrating various cues for depth perception. These cues are numbered and discussed in the text.

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Dosher, Sperling, and Wurst (1986) and Schwartz and Sperling (1983)

tested the hypothesis that variation in brightness induces a sensation of

depth by assuming that the brighter part of a computer-generated, luminous,

wire-frame object would be perceived to be in the foreground. They found that

the brighter parts of an object appeared closer to the observer than the

dimmer parts. Dosher et al. (1986) define this cue as Proximity Luminance

Covariance (PLC) (see also Section 3.6).

Figure 2.1: #1: The difference in luminance along the runway serves as

a depth cue. The foreground is brighter and more clearly defined.

Constraints:

*Using brightness to code discrete levels of depth appears to be ambiguous

 regarding the observer's perception of the object's closeness.

*Provides relative, but not absolute, distance information.

2.1.2 Aerial perspective. Desaturation and/or the addition of the

environment's ambient hue to an object's color can affect the perceived depth

of an object, particularly of relatively distant objects. Desaturation of an

object's objective color is caused by the atmospheric scattering of light,

(resulting in a grayer color). The addition of the ambient hue, usually blue,

is again a result of the increased atmosphere present between the observer and

the perceived object. Hence, desaturation and a bluish hue would convey

information that objects are at greater distance.

Figure 2.1: #2: The mountains in the background would show these

effects.

Constraints:

*Provides relative but not absolute distance information.

2.1.3 Shadows and highlights. The perceived depth of an object (the

surface of an object, or the surface upon which the object casts its shadow)

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may be affected by the presence of shadows or highlighting on the object itself or upon surfaces contiguous with the object.

A shadow may be <u>attached</u> (cast by and falling upon the object itself) or <u>cast</u> (falling off the object onto a background). As a depth cue, an attached shadow shows the characteristics and shape of an object's surface, particularly by indicating whether a given area is extended or indented from the surrounding surface (Weintraub & Walker, 1968; Cavanagh, 1987). Perception of a two-dimensional shape (e.g., an ellipse) as a 3D object (an ellipsoid) is created with the use of attached shadows (Todd, 1985). A cast shadow influences perception of the surface upon which an object casts its shadow, as well as the judgment of distance of an object (Rock, Wheeler, Shallo, & Rotunda, 1982).

Figure 2.1: #3: Attached shadows are shown on the sphere and right wall of the first control tower, and on the lower right of the runway. The latter shows an indentation in the surface of the runway.

Figure 2.1: #4: Cast shadows are shown near both towers. The cast shadow of the closer tower indicates a bump in the surface of the runway. The angle between the two shadows indicates the relative positioning of the light source and the two towers in 3D space. To the extent that this angle is greater than zero, the towers are farther apart relative to their distance from the source.

A light source may be <u>specular</u> (i.e., roughly parallel rays of light from one source) and vary in intensity and position, or it may be <u>diffuse</u>. A highlight is a strong "spot" of reflected light from a specular source. The location of a highlight on an object's surface is dependent on the position of both the light source and the observer. If the object or observer moves, the location of the highlight will shift across the surface of the object

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(Kennedy, 1974). A highlight will move in the same direction as the moving light source or observer across a convex surface, in the opposite direction across a concave surface. Its intensity and the qualities of the object's surface determine the kind of highlight that will be perceived (e.g., a simple bright spot, a bright spot encircled with a diffuse coma). Diffuse illumination generally does not produce shadows, though it allows perception of the entire face of the object, and its contour, against the background.

Figure 2.1: #5: A highlight is present on the sphere of the first tower. As the observer moves past the tower (e.g., flying over the runway) this highlight will move around the sphere in the observer's direction.

Constraints:

*Light, as a specular source, is assumed to come from above, not from the side or bottom of an object (Berbaum, Tharp, & Mroczek, 1983; Haber, 1980). This influences perception of: i) attached shadows: In general, if an area's lower half is shaded, this area is seen as extending forward; if an area's upper half is shaded, the area is seen as indented (Rock, 1975); ii) highlights: Highlights produced by light from above induce greater depth effects than highlight from a side source (Berbaum et al., 1983).

*The functional use of cast shadows as a relative depth cue depends on a specular light source located relatively close to the objects (e.g., a flare or spotlight, rather than the sun). This is necessary to cause a distinguishable difference between the angles of the objects and their respective cast shadows (Rock et al., 1982). Otherwise, cast shadows only provide information of the immediate area (Rock, 1975).

*The qualities of the object's surface (shiny or dull) will affect the amount cf light reflected from the object (and therefore its shading). A curved surface is perceived as more curved if its surface is shiny rather than dull

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(however, judgments concerning the degree of curvature are not more accurate)
(Todd & Mingolla, 1983).

2.1.4 Color. Differences in color--that is, hue, saturation and brightness- affect an object's perceived depth.

[Also see Aerial Perspective, 2.1.2 above]

Egusa (1983) examined the effects of brightness [see 2.1.1 above], hue, and saturation on perceived depth. Concerning hue, Egusa compared depth perception of two adjacent regions. In one condition achromatic hues (black, gray, or white) were compared with chromatic hues (red, blue, or green). In another condition, chromatic hues were compared with other chromatic hues. Over both conditions, red was judged to be closest to the observer followed by green, and then blue. Concerning saturation, as the difference in saturation levels between the two regions increased, so did the perceived distance separating the regions. However, the direction of perceived depth between saturated and desaturated levels differed across hues.

Egusa hypothesized that the usefulness of color as a depth cue arises from the chromatic aberration of light. As different wavelengths of light pass through the lens of the eye, these wavelengths bend and leave the lens at different angles (much as a prism creates a "rainbow"). This in turn causes different focal points within the eye for the different wavelengths of light (and therefore a need for differential accommodation of the lens). This is called chromatic aberration.

Constraints:

*Ambiguity of saturation differences.

*Does not provide absolute depth information.

*Color is salient, and by color coding different objects or depth planes this may signal unwanted and irrelevant information. For example, the choice of

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red to signal "close," may also be perceived as "danger."

*Ineffective and/or misleading for 7% of the male population whose vision is color deficient.

*Unreliable in varying conditions of ambient illumination.

2.1.5 Texture gradients. The perceived depth of a surface (for example, the earth's terrain)--whether flat, slanted, or curved--is affected by its texture.

Most objects perceived visually by human observers contain textured patterns across their surfaces. This texture is defined by the size and spacing of the elementary features of which it is composed. This surface, when viewed at an angle other than $0°$ or $90°$ results in a texture gradient. A typical example is the viewing of a large field of grass. The elementary unit is a blade of grass. The "gradient" is the change of texture perceived as one looks from one's feet up to the horizon. When texture gradients are used to convey a sense of depth, the viewer assumes that the elementary texture units are of roughly the same size and are approximately equally spaced across the surface (Cutting & Millard, 1984; see also Braunstein. 1976).

Cutting and Millard distinguished between three static gradients concerning depth perception: i) perspective gradient; ii) compression gradient; and iii) density gradient. Couched in an analogy of viewing a hallway with a tiled floor:

i) Perspective gradient is measured by the change in the x-axis width of an elementary feature (e.g., a tile).

ii) Compression gradient is the ratio of y/x axes measures of the elementary feature (Figure 2.1: #6).

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iii) _Density gradient_ is measured by the number of tiles per unit of visual angle (Figure 2.1: #7).

Linear perspective is a special case of a perspective texture gradient when the elements involved are all of objectively equal sizes and objectively consistent density. A particularly strong effect occurs when these elements form parallel lines on the actual surface that is viewed; railroad tracks are a typical example. (Figure 2.1: #8: Linear perspective of the parallel sides of the runway.)

The perception of slant of a f, t surfrce is guided largely by the perspective gradient (65%), to a lesser degree by the density gradient (28%), and least by the compression gradient (6%). The perception of curvature in a surface is overwhelmingly guided by the compression gradient (96%), with the perspective and density gradients providing very weak influences (2% apiece) (Cutting & Millard, 1984). When linear perspective is used in the construction of 3D objects or scenes, these are described as using _polar projection_. When it is not, a _parallel projection_ is created (see Figure 2.2).

Constraints:

*Perspective works best for regularly textured surfaces and poorly for random dots or random shapes of irregular size._

*Subjects estimating the degree of slant from a photograph systematically underestimate the objective slants of the surfaces (Gibson, 1950). That is, they estimate the surface to be more closely orthogonal to the line of sight than is the case. This effect is significantly greater for irregular surface textures than for regular surface patterns._
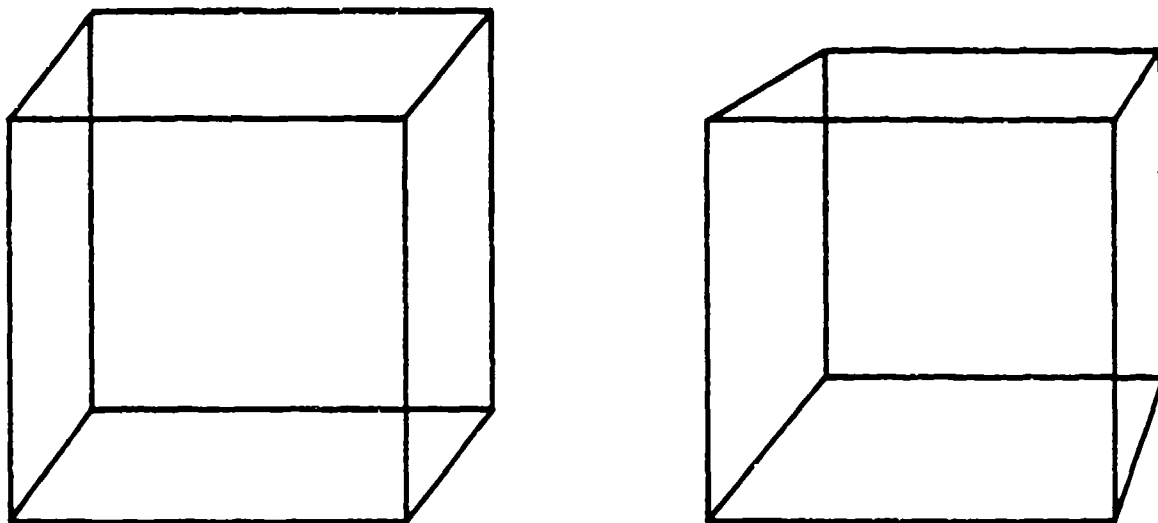
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Figure 2.2   Examples of a wireframe cube in parallel projection (left) or
polar projection (right).

2.2 Occlusion or Interposition

The perceived depth of objects (or parts of objects) is affected by the apparent interposition of these objects relative to the observer's viewpoint.

The occlusion/interposition cue results from the perceptual organization of the objective image by the observer. An assumption is made that the more distant object does indeed continue behind the occluding object. Hence, more familiar objects increase the effectiveness of occlusion (Schiffman, 1982; Ittelson & Kilpatrick, 1952).

Figure 2.1: #9: Occlusion of the mountains and the rightmost jet.

Constraints:

*Occlusion is necessarily an ordinal and relative depth cue. For example, the use of occlusion to represent a rotating sphere allows for perception of only ordinal depth (i.e., which surface of the sphere is closer), and does not assist in the perception of the object's shape/depth in 3D space (Andersen & Braunstein, 1983).

2.3 Object Size

The perceived size of an object can serve as a depth perception cue in a number of ways.

2.3.1 Size-distance invariance. This cue concerns the perceived depth of objects based on their assumed or perceived size, and the size of the visual angle subtended by their retinal image. This relation may be expressed by the approximate formula: Size - Visual Angle x Distance. When true size is known (or estimated), then the expression can be used to calculate the distance of an object from the observer. When distance is known (from other cues) then the formula provides the means for deriving a perceived size. The relation has two general implications:

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i) Objects of a greater visual angle are perceived as closer than those of a smaller angle.

Figure 2.1: #10: The rightmost building appears to be closer than the smaller building to its immediate left.

ii) Objects of the same visual angle are perceived to be the same distance away.

Figure 2.1: #11: These two jets are the same objective size and appear the same distance away.

Constraints:

*Applicable primarily to familiar objects whose true sizes are known.

2.3.2 **Size by occlusion**. Perceived object size is supported by occlusion, with object size estimated by the number of elementary texture units of a background surface occluded by that object (Gibson, 1966). The perceived distance of the object then becomes a function of the visual angle it subtends (since Perceived size - Visual angle x Perceived Distance).

Figure 2.1: #12· The upper jet occludes a greater number of texture elements and is therefore perceived as more distant.

Constraints:

*A relative distance cue is reliable only if texture of the surface is uniform behind all objects.

2.3.3 **Familiar size**. Familiarity of an object to the observer can serve as a cue for absolute depth perception by influencing perceived object size.

A familiar object tends to maintain a constant perceived size, no matter what its objective visual angle (Schiffman, 1982). The perceived distance of that object then becomes a function of the visual angle it subtends (since Perceived size - Visual angle x Perceived Distance) (Ono, 1969).

Figure 2.1: #13: The five jets in flight are assumed to be all of equal size. Since the leftmost jet subtends the smallest visual angle of the five, it will be perceived as the farthest away.

Constraints:

Potentially misleading when used with similarly shaped objects that might have very different sizes (e.g., runway lengths, aircraft).

2.4 Height in the Visual Field

The vertical position of objects and parts of objects in the visual scene--from the observer's viewpoint--can act as a depth perception cue. The higher an object is in the visual field, the farther it appears to lie from the observer (Berbaum et al., 1983). This cue is based on the observer's assumption that the "ground plane" upon which the observer stands extends outward horizontally to the horizon (Rock, 1975). That is, in a typical visual scene, it is assumed that the foreground is low and the horizon high. Conversely, objects that are horizontally adjacent will be perceived as equidistant (Schiffman, 1982; see also Gogel, 1965).

Figure 2.1: #14: These two jets subtend the same visual angle, but the objectively higher jet appears farther away (therefore, according to the size-distance invariance cue, it also appears to be larger).

Figure 2.1: #15: The jet and the one building are horizontally adjacent and will appear as equidistant.

Constraints:

Depends on the "standard" viewing perspective: looking down on objects. Unreliable and misleading when viewing objects from below (i.e., as in viewing other aircraft in the airspace above, or viewing submarines or ships from a viewpoint below).

2.5 Motion

Sufficient motion for the perception of depth may result from any movement of the observer (in entirety or just head movement) and/or movement of the object(s). This motion will alter the relative distance and the original orientation between the observer and the object(s).

2.5.1 **Motion perspective**. This cue concerns the depth perception of objects from motion. Motion perspective allows the perception of the relative distances, velocities, and locations as well as the direction of movement of these objects, as the observer's viewpoint of the environment changes. The greater the objective distance between the objects, the greater is the shifting of their images relative to one another with observer movement.

Figure 2.1: #16: As the observer moves forward, over the runway, the lower building--now partly obstructed by the first control tower--will first disappear and then become visible. The relative distance and position of the two buildings will become increasingly clear.

Motion parallax is a unique case of motion perspective. It describes the effects of a relative, lateral motion between the observer and the object(s). Objects closer to the moving observer are usually perceived to be moving faster than those objects at a distance. Thus an observer may move his head from side to side to determine which of two objects is closer. The apparent direction of these objects and their perceived speed, however, are a function of the observer's fixation point (see Figure 2.3) (Schiffman, 1982).

Rogers and Graham (1979) examined motion parallax produced by either movement of the display or movement of the observer. They found that self-produced movement by the observer resulted in a greater sensation of depth. However, with larger amounts of relative movement, the amount of perceived depth was less than expected. Rogers and Graham also emphasized the

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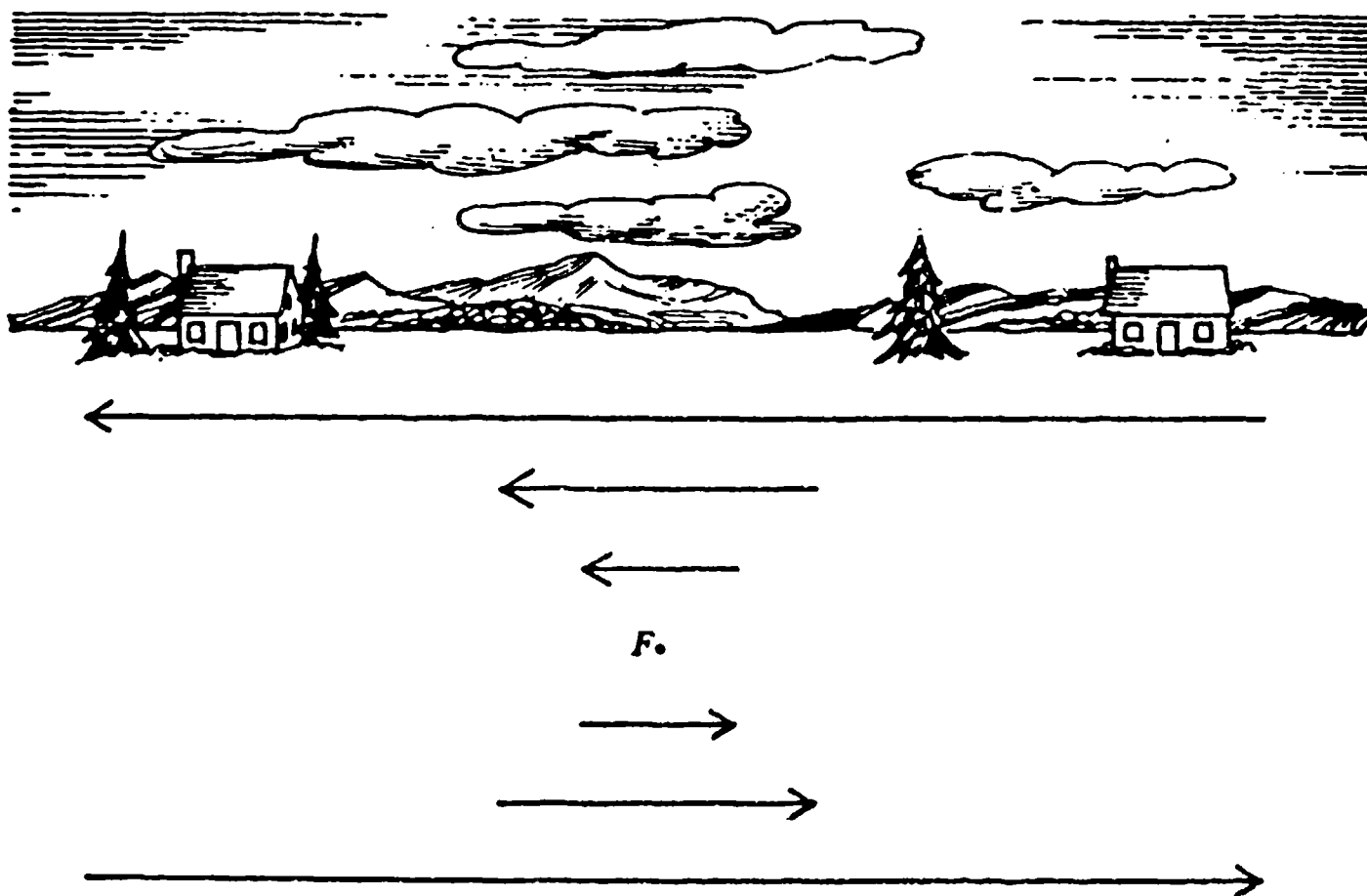
Figure 2.3. Schematic diagram of motion parallax. If an object located at F
is fixated while the observer moves to the left, the images of the nearer
objects appear to move to the right whereas farther objects seem to move to
the left. The length of the arrows indicates that the apparent velocity of
objects in the field of view increases in direct relation to their distance
from the fixation point (based on Gibson, 1950), from Schiffman, 1982.

importance of a complex display with many objects and features producing a strong sensation of depth.

<u>Constraints</u>:

*Ono, Rivest, and Ono (1986) examined depth perception from motion parallax created by self-produced observer movement. This movement activated sensors positioned on the head which drove aspects of the display. As viewing distances increased, observers lost the perception of depth and saw only a flat, two-dimensional motion of the objects across the screen of the CRT. Loss of perceived depth was a function of individual differences, the degree of disparity used, and the viewing distance.

*Motion parallax is primarily a relative depth cue (Rogers & Graham, 1979; Farber & McConkie, 1979), although it may also provide some absolute distance information (Landy, 1987).

    2.5.2 <u>Object perception</u>. This cue concerns the perception of depth which describes an individual object's 3D structure from its rotation. This process is also called the "recovery of structure from motion" (Braunstein, 1986).

    The <u>kinetic depth effect</u> (KDE) describes the perception of a 3D object from a 2D stimulus; this stimulus is the flat shadow of a rotating 3D wire-frame object, typically a wire cube, cast upon a translucent screen before an observer. Rotation of the object is around the X or Y axis of the screen (i.e., an axis orthogonal to the Z axis). The perception of the object as 3D will emerge only when the object is put into motion.

<u>Constraints</u>:

*The shadow of the rotating object may be projected onto the screen in parallel or polar fashion (see Figure 2.2). Braunstein (1986) states that kinetic depth from parallel projection "provides information about object

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shape but leaves depth order ambiguous"; the use of polar projection
introduces a perspective gradient and allows the perception of depth order.
For a perception of depth order with the use of parallel projection, other
cues, such as stereoptic disparity, must be included (see Richards, 1985).
Todd (1984) states however ". . . it is yet to be determined which degree of
perspective results in the most precise perceptual specification of an
object's 3D structure."

*Integration of the changing two-dimensional information over time is
necessary. The longer the viewing time, the more accurate the perception;
shorter viewing times often lead to the perception of flatter-than-correct
objects (Ullman, 1979; Lappin et al., 1980; Green, 1961; White & Meuser,
1960).

*The kinetic depth effect provides only relative depth information to the
observer; that is, the 3D shape of the object in space is conveyed, but not
its absolute distance from the observer (Landy, 1987).

2.6 Muscular Sensations

        The muscles that control different aspects of the visual system provide
proprioceptive information that can serve as depth perception cues.

        2.6.1 Accommodation. This cue concerns the depth perception of
objects, which results from the different levels of adjustment of the lens
(accommodation) necessary to bring objects of different objective distances
into focus on the retina. The focal length of the lens is altered by changing
the shape of the lens. The normal range of accommodation is about 20 feet
(6m) to about 4 in (10.2 cm) (Brown, 1965).

        i) Viewing a scene monocularly through an "artificial pupil" eliminates
the need for accommodation of the lens to focus on objects of different

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distances. Objects at all distances will be in focus on the retina (Rock, 1975).

ii) <u>Collimation</u> is the optical technique of passing light rays through a lens in such a way that they are parallel when reaching the lens of the eye. This eliminates the need for accommodation.

<u>Constraints</u>:

*Accommodation is affected not only by the distance of the observed object but by low ambient illumination or reduced and degraded visual stimulation which occurs when pattern, contour, and contrast detail are absent from the visual field (Iida, 1983; Schiffman, 1982). Under these conditions, when there are few identifiable contours to act as a cue for the appropriate focus, accommodation of the lens deviates from an accurate focusing mechanism (and hence, distance cue) towards a resting state (see also Simonelli, 1983).

*Accommodation response is affected by an observer's nearsightedness (myopia), farsightedness (hyperopia), and age (Simonelli, 1983). For an observer with myopia, accommodation of the eyes will occur or "rest" at a nearer distance than for an observer without myopia, even after correction with artificial lenses (glasses or contacts). As an observer's age increases, the resting point of accommodation will again move inward towards the observer. The location of an observer's resting point is important because accommodation is affected by both this distance and the distance of the object being observed (Simonelli, 1983).

*Accommodation is affected by certain emotional states (Schiffman, 1982).

*When both accommodation and convergence cues (2.6.2) respond to the same stimulus they act fairly well as depth cues up to approximately 2 m but are of limited usefulness beyond this point (Wallach & Floor, 1971).

2.6.2 <u>Convergence</u>. This cue is based on the proprioceptive feedback

from the muscles that rotate the eyes inward (cross-eyed) or outward to fuse the image of an object on proper, corresponding locations of the two retinas. The degree of convergence is defined by the angle between the axes of the separate eyes and, therefore, is inversely proportional to distance. When viewing a distant object, the axes are nearly parallel and convergence is low. When viewing a close object, convergence of the eyes increases.

Constraints:

*When both accommodation and convergence cues respond to the same stimulus they act fairly well es depth cues up to approximately 2 m but are of limited usefulness beyond this point (Wallach & Floor, 1971).

*Convergence provides less accurate informaticn with monocular viewing, but is still available to some extent when the head angle is fixed.

2.7 Binocular Effects

These cues result from the use of two separated eyes. Because of this separation, the two retinas receive slightly different images of the visual scene. Convergence of the two eyes is necessarily a binocular cue (see 2.6 Muscular sensations above).

2.7.1 Convergence. The degree of convergence, a muscular cue, is also a binocular cue, and is described in Section 2.6.2.

2.7.2 Disparity. This cue concerns the reconciliation of noncoincident (disparate) images on the two retinas into a singular image of an object perceived at some depth from the observer.

Assume that two objects of equal size are located in the environment and are within the visual field (see Figure 2.4). The relative locations of these objects on the left and right retina will differ due to the separation of the two eyes. How they will differ depends on the absolute and relative depth distances of the objects, and their horizontal separation. The perspectives
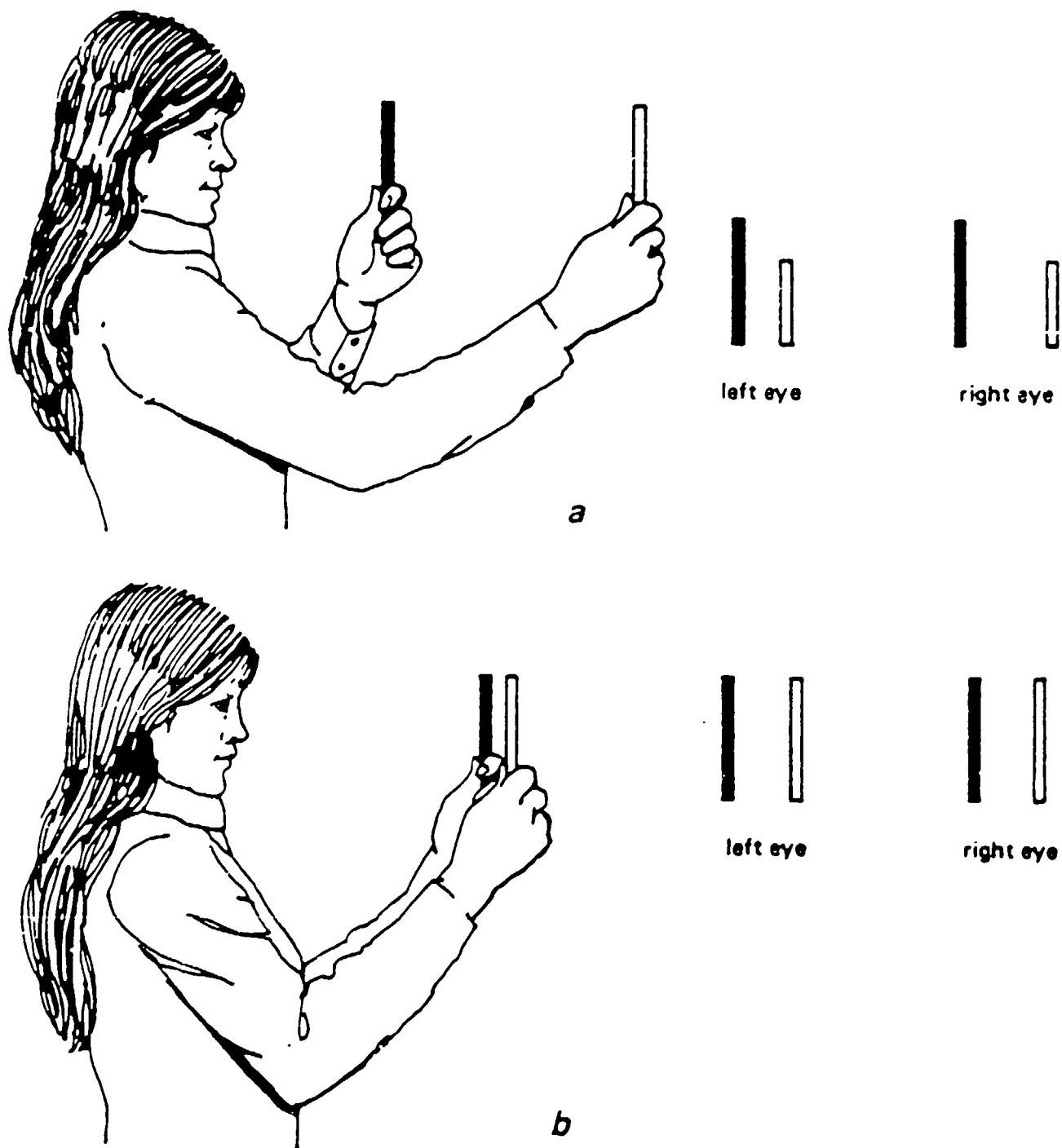
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Figure 2.4. Demonstrates binocular disparity. Note the larger differences between the left and right view when the distance between objects is great (top), relative to when it is not (bottom) (from Rock, 1975).

of this scene for the different eyes are shown in Figure 2.4. Note that the horizontal distance between the two objects differs, depending on the eye's viewpoint. If this disparity across the images of the separate eyes is not too great, the visual system will "assume" the two images to both fully represent the visual scene. The two images are then fused to form the perception of one visual scene, comprising two objects, with a sense of depth. If, however, the disparity of where the images fall on the two retinas is too great, double images may be seen. This may occur in two ways, through crossed or uncrossed disparity. Fixation of a near object will cause the projection of a distant object's image to fall on the nasal sides of both retinas. Therefore the right eye will see the far object as displaced to the right of the near object, the left eye to the left. This condition is called uncrossed disparity. Likewise, fixation of a distant object will cause the right eye to see the near object as displaced to the left, the left eye to the right of the fixated object (the unfocused image falling on the temporal side of both retinas). This condition is called crossed disparity (see Figure 2.5).

To create an artificial disparity, five methods have generally been used: mirrors, lenses, rapid alternation of the left and right views (time multiplexing), colored light (an anaglyph), and polarized light (a vectograph) (Rock, 1975). The use of colored or polarized light requires the use of spectacles with different colored or polarized lenses for each eye. The apparatus shown in Figure 2.6 will generate the view described above. Note the difference in relative location of images a and b across the two retinas. Each of these techniques presents slightly offset images to the two separate eyes, and the degree of offset is inversely proportional to the intended distance. This degree of offset is typically expressed in minutes and seconds
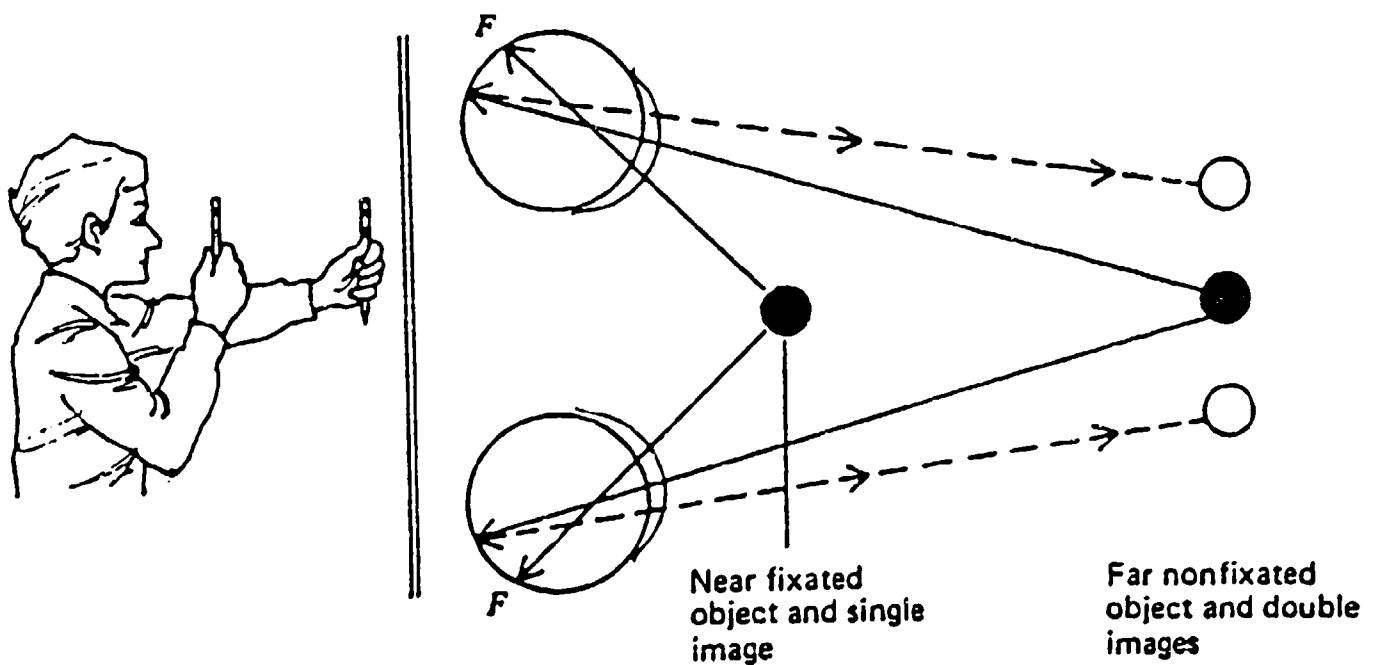
Figure 2.5. Double images and disparity. Holding a relatively near and far
object as indicated and fixating on the near object will produce a single
image of the near object and double images of the far object. The image of
the near object falls on the foveae (F) of both eyes whereas the images of the
nonfixated, far object fall on the nasal part of each retina. The solid lines
represent the light reflected from the two objects: the dashed lines indicate
the apparent paths of the projected   images from the far, nonfixated object
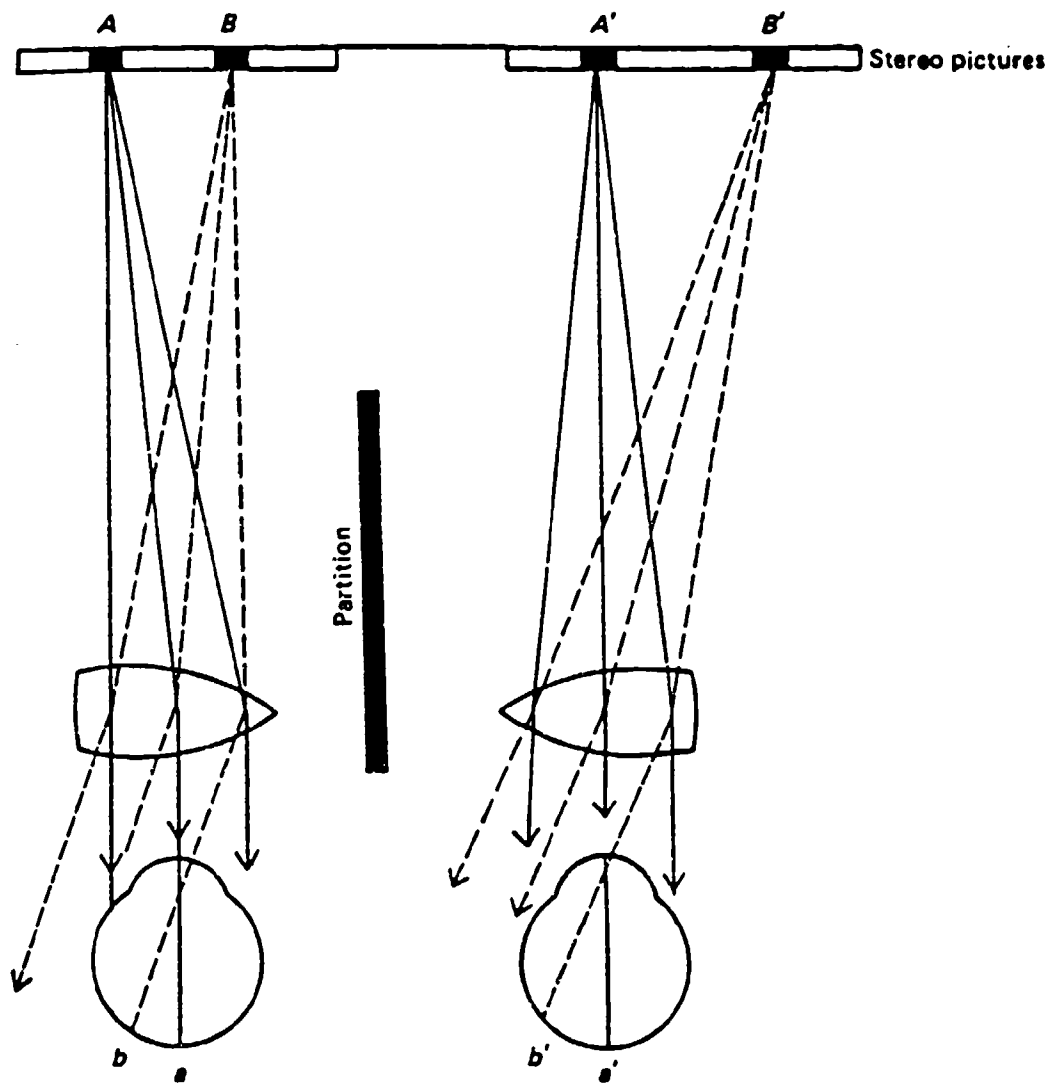(from Kimble, Garmery, & Zigler, 1980, p. 80).

Figure 2.6. Construction of a stereogram through optics (Rock, 1975).

of visual angle. At one meter distance, differences in depth between objects of a few seconds of visual angle can be resolved (see Section 4.2 for a discussion of stereoscopic display technology).

<u>Constraints</u>:

Large amounts of disparity will result in the perception of double images. If a continuum of disparity values is present, these large disparities will be better tolerated (Burt & Julesz, 1980). Yeh and Silverstein (1989) measured disparity thresholds while controlling for possible assistance from eye convergence, using a "time-multiplexing" system. Threshold measurement is defined as the horizontal offset between the left and right eye images, converted into visual angle. For crossed disparity, the threshold was 27.11 minutes of arc, but only 24.21 for uncrossed disparity.

The effects of "cross-talk" between the two images sent to the different eyes (Yeh & Silverstein, 1989), can sometimes produce "ghosts." This will occur with multiplexing imaging techniques when the display phosphor does not decay rapidly enough; therefore, a "ghost" of the right eye images remains on the display when the left eye views and vice versa. This ghosting appears sensitive to the color of the display and is minimized with red or amber images.

Only horizontal disparity in the visual scene will produce depth perception. Vertical disparity will result in the suppression of one eye's image or in the perception of a double image. This constraint results from the horizontal placement of human eyes (Rock, 1975). Hence, artificial stereo displays must be viewed with the orientation of the head orthogonal to the direction of disparity. Therefore, a stereo-pair display is also not appropriate for multiple-observers or off-angle viewing (Williams & Garcia, 1989a,b).

The "virtual 3D environment" of stereo-pair displays (e.g., from Tektronix,

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StereoGraphics) cannot be fused by 10% of the population. However, this problem becomes less acute if the images are dynamic (Tittle, Rouse, & Braunstein, 1988).

*Using artificial stereoscopic displays, different kinds of surface textures/patterns will interact with an observer's ability to accurately perceive stereoptically presented information. Random textures allow better depth perception than regular patterns; horizontal-vertical textures tend to be seen as flatter and farther away than diagonal ones; and continuous textures tend to be seen closer than discontinuous ones (Ninio & Mizraji, 1985).

*Stereopsis is most effective in near space, for distances reachable by hand. Objects that are far away produce more or less similar disparities: "stereoscopically, they are at the same distance" (Prazdny, 1986). However disparity may be used to artificially simulate depth differences of distant objects (Zenyuh, Reising, Waichli, & Biers, 1988).

2.8 Nuisance Cues

The previous discussion has described a number of cues to distance. From the perspective of the display designer, these cues are important in two different capacities: as sources of relevant information to be incorporated into display design, and as unwanted "nuisance" variables, whose effects may need to be filtered out or compensated. In the first case we consider, for example, the importance of including depth cues such as stereopsis or texture to create a compelling sense of depth. In the second case, we consider a situation in which a cue inappropriately signals a different sense of distance from that intended. As one example, a rectangle wire frame like that shown in Figure 2.6 might be used to provide a flight path "tunnel" in the sky (see Section 4). However, the cue of height in the visual field will signal that

the near end is actually farther away when (as is the case here), the tunnel is viewed from beneath. As a second example, collimation may be employed to create a sense of depth from the cue of accommodation. But if there are prominent marks on the display surface, these marks may "signal" to the eye muscles a point on the display surface upon which the two eyeballs will converge. Hence, the "nuisance" convergence cue will provide information that the display is near, partially neutralizing the effect of accommodation.

This second example relates to a set of characteristics that Braunstein (1976) refers to as cues to flatness. While the previous section has described properties of the displayed information that can create a more compelling perception of depth, Braunstein emphasizes properties of the surrounding display frame and surface that can detract from this perception by signaling to the observer that the display actually is a flat two-dimensional surface. These cues to flatness can include the physical frame surrounding the display, and any identifiable marks on the display surface. Techniques to reduce cues to flatness include monocular viewing, viewing through a dark tube at a greater distance, viewing through a collimated lens, and viewing when the background is not illuminated. Such techniques greatly enhance the perception of three dimensionality (Larish & Flach, in press; Palmer & Petitt, 1977).

3.0 MULTIPLE CUE INTERACTION

In this section we review individual studies that have examined the relative strengths of various depth cues. In these studies, two or more cues are used to portray a 3D image. These separate cues, however, could present information concerning the object's location or orientation in depth that is either _conflicting_ or _congruent_. Studies of the first class, which may be described as cue tradeoff studies, assess which cue "wins", when two are placed in conflict. Studies of the second class, which may be described as cue compellingness studies, assess the compellingness of a sense of depth, created as different cues are added.

One focus of this review is to establish the best "model" for cue combination. An _additive_ model is one in which the sense of depth is an additive function of the number of cues employed (Bruno & Cutting, 1988). The cues may have equal weight, or some may be dominant over others. A nonadditive model is one in which the contribution of a given cue to the sense of depth will differ, depending on the number or kind of cues already present. The effect may either be _subtractive_ (a cue's influence is diminished) or _super-additive_ (its influence is enhanced).

The sections are organized as follows: Section 3.1 reviews the work done with stereopsis in combination with other depth cues which are either static (3.1.1) or dynamic (3.1.2). Section 3.2 reviews studies on the effects of motion; Section 3.3 reviews studies on the effects of shadows, attached and cast; Section 3.4 addresses the cue of height in the visual field; Section 3.5 covers studies on the effects of a surface's texture pattern; Section 3.6 addresses the effects of object luminance (the Proximity Luminance Covariance, PLC); and Section 3.7 presents a summary, and the conclusions drawn from the multiple cue studies that have implications for the display designer.

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3.1 Stereopsis

3.1.1 Stereopsis with static cues. Van der Meer (1979) investigated depth perception when the depth cues of binocular disparity and perspective (actually a converging texture gradient with decreasing y-axis heights to represent distance) presented either congruent or conflicting depth information. Stereopsis was created with the use of an aniseikonic lens (lenses which magnify an image in the horizontal meridian) before one eye (see Gillam, 1968). Perspective was represented by the decreasing height of vertical bars in the pattern viewed: the bars were 15 cm (no perspective effect), 12, 8.3, 5, or 1.7 cm (the strongest perspective effect). The observer's head was kept stationary. As expected, when the two cues indicated an increasing depth, depth perception increased. When the two cues presented conflicting information, 12 of the 18 observers used stereopsis, four used perspective, and two used the stereoptic cue in all but the two strongest perspective conditions. The effects of stereopsis and perspective in this experiment were additive: with increasing amounts of perspective, whether congruent or in contrast to the orientation of the stereopsis used, the amount of depth perceived increased/decreased linearly.

In a lengthy review of research on slant perception, Braunstein (1976) concludes that contour convergence--a sort of linear perspective--and stereoscopic viewing are roughly additive in their effects on the perception of slant.

Kim, Ellis, Tyler, Hannaford, and Stark (1987) examined depth perception when the depth cues of binocular disparity and perspective presented only congruent information. Observers were asked to track a target moving in three dimensions. In the first condition, the target moved above a flat, floor-like grid which facilitated the perception of the perspective depth cue; the target

was connected to the grid by a vertical reference line. In other conditions, either the grid, the reference line, or both were absent from the display. All these conditions were shown either with or without stereopsis. Overall, 3D tracking was more accurate with use of the stereoscopic display, with or without the reference line or grid. However, with the reference line and grid present (and placement of the observer's viewpoint at an elevation of 45° and an azimuth of 0° or 45° to the grid), tracking was as accurate for monoscopic viewing with perspective as under stereopsis.

Braunstein, Andersen, Rouse, and Tittle (1986) examined depth perception when the depth cues of binocular disparity and occlusion presented either congruent or conflicting information. The computer display of a rotating sphere with randomly placed, irregular pentagons on its surface was stereoptically presented to observers using a "Brewster stereoscope," (a prism stereoscope, Braunstein, 1986). The sphere itself was either opaque--leading to "edge occlusion" as the texture elements (the pentagons) disappeared and appeared over the horizons of the sphere, or transparent--leading to "element occlusion" as the texture elements on the closer surface of the sphere moved between the observer's viewpoint and the texture elements on the far side of the sphere. The direction of the sphere rotation was indicated by both stereopsis and either one or the other type of occlusion, with the two cues presenting either congruent or conflicting information. When both stereoptic and occlusion cues represented the same direction of rotation in depth, 94% of the judgments matched this rotation with the use of element occlusion and 91% of the judgments matched with the use of edge occlusion. When the stereoptic and occlusion cues represented opposite directions of rotation, the percent of judgments following the stereoptic information fell to 81% with the use of element occlusion and to 36% with the use of edge occlusion. Hence, edge

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occlusion is a more dominant cue than element occlusion. [Note: Andersen and Braunstein (1983) found that the occlusion of shapes (e.g., squares, pentagons) is more effective than the occlusion of small texture elements (e.g., dots).]

In a similar study, Tittle, Rouse, and Braunstein (1988) presented subjects with the image of a rotating cylinder viewed stereoscopically. The cylinder was covered with texture elements and was opaque, so that elements on the rear face of the cylinder would be obscured by the front face (interposition). Subjects judged the direction of rotation of the cylinder when stereopsis cues and interposition cues regarding the front and back face were in concordance and in conflict. In the conflict condition, 91% of the judgments were dominated by interposition.

Cavanagh (1987) placed stereopsis and interposition in conflict as observers viewed two overlapping wire frame squares (the front and back frames of a "Necker cube"). Using subjective reports, he found that observers were roughly divided regarding which cue dominated perception.

Dosher et al. (1986) examined depth perception when the depth cues of binocular disparity and proximity luminance covariance (PLC) presented either congruent or conflicting information. The image of a luminous, wire cube was presented on a CRT. The brightness of the individual lines that formed the cube were varied as a function of that line's objective distance from the observer's viewpoint (the displayed intensity of a line decreased as an inverse proportion to the distance of that line). All lines that formed the "wire cube" could be seen. The image of the cube was shown stereoptically using a system of mirrors and baffles; a constant degree of perspective (nonpolar) was used throughout the experiment. Observers saw either a stationary cube, a stationary cube which then began rotating, or just a

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rotating cube. Disparity determined depth perception for all four observers for the stationary and stationary-then-rotating cube images. For depth perception of the rotating-only cube, stereo disparity was a strong cue for only two of the observers. The effects of PLC varied widely across the four observers. Overall, stereopsis was usually the stronger cue (than PLC), but the relative importance of a cue appeared largely situation dependent.

Bulthoff and Mallot (1988) examined depth perception when the depth cues of binocular disparity, attached shadow (i.e., shading), and highlights presented only congruent information. The surface quality (smooth versus faceted) was also manipulated. The static 3D image of an ellipsoid was presented on a CRT. The ellipsoid's surface was either smooth, resulting in a gradual attached shadow (shading) across its surface, or faceted, resulting in visible edges (sharp changes in shading) within the attached shadow. The light source was either diffuse or specular (creating a highlight on the object's surface) and was positioned at the observer's viewpoint. The static ellipsoid was also presented with or without binocular disparity (using interlaced images viewed through a shutter stereoptic system). The amount of perceived depth of the ellipsoid ranged from high (almost matching the 3D shape of the object) to low (the inaccurate perception of a very shallow ellipsoid) in order with the following combinations of cues: binocular disparity and shading with edges; binocular disparity and shading without edges (that is, a smooth shadow); no disparity and shading with edges; no disparity and smooth shading. [The authors noted that the use of edges--with their sharp changes in shading--resulted in a significant increase in perceived depth as compared to the use of gradual shading.] (The use of shading without edges reduced perceived depth by about 25%.) The use of diffuse or specular lighting did not make a difference in perceived depth.

In a second aspect of the same experim ..t, Bulthoff and Mallot (1988) examined depth perception when the depth cues of binocular disparity and the location o the light source were varied. The surface quality (smooth versus faceted) was also manipulated. The static 3D image of a smooth ellipsoid was presented on a CRT. A diffuse light source illuminated the ellipsoid from one of two locations: from the upper left or lower right, both in front of the object (at +-14° azimuth and +-13.6° elevation from the line of view). The ellipsoid was also presented with or without binocular disparity (using interlaced images viewed through a shutter st~~optic system). The nonilluminated side of the ellipsoid (the dark, shadowed region) was perceived as flat. When the light source was positioned to the lower right of the object, the ellipsoid was occasionally perceived as a concave surface (this is due to the implicit assumption by the observer that the light source is located above th visual scene, casting shadows downwards, as is usually the case). The use of binocular disparity prevented this reversal.

3.1.2. <u>Stereopsis</u> <u>with</u> <u>motion</u>. Braunstein et al. (1986) examined depth perception when the depth cues of binocular disparity and a velocity gradient presented either congruent or conflicting information. A surface consisting of two slanting planes meeting at a horizontal midline was presented stereoptically to observers using a Brewster stereoscope. The apex of this surface could either be pointing towards or pointing away from the observer. Randomly placed dots moved across this surface horizontally. The speed of an individual dot depended on its distance from the apex and its proximity to the observer. The varying speeds of all the dots comprised the velocity gradient. The direction of the apex was indicated by both stereopsis and the velocity gradient, with the two cues presenting either congruent or conflicting information. Subjects judged whether the apex pointed toward (near) or away

(far) from them. When the two cues were congruent, judgments were highly accurate. When stereoptic and velocity gradient cues were placed in conflict, the number of judgments following the orientation represented by the stereoptic cue was significantly reduced. When the velocity gradient represented a near apex, the proportion of judgments following the stereoptic cue dropped from approximately 93% to 80%; when the velocity gradient represented a far apex, the drop was from approximately 89% to 52%. Higher velocity of movement created a greater influence of velocity gradient on perceived depth.

Tittle and Braunstein (1989) examined subjects' ability to recover the perceived structure of objects (a rotating cylinder) from their motion with stereo viewing, and concluded that motion had a super-additive effect. That is, the effects of stereoscopic viewing were enhanced under motion.

Prazdny (1986) examined depth perception when the depth cues of binocular disparity and motion presented only congruent information. A CRT display was filled with a pattern of black and white dots, with equal amounts of each randomly placed. In one condition, a 3D object was portrayed as a moving area of alternating black and white dots. In a second condition, a 3D object was portrayed within two patterns of black/white dots which were viewed stereoptically. The perceived shape of the 3D object was determined by the motion of the object (i.e., the "kinetic depth effect") while its location in depth was determined by disparity.

Summary of these studies will be presented and discussed in Section 3.7.

2.2 Motion

Todd (1985) examined depth perception when the depth cues of motion (of a rotating object) and attached shadow presented only congruent information.

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A computer-generated ellipsoid was rotated about its vertical axis. The surface of the ellipsoid was either shaded (with an attached s adow as if the light source were located at the observer's viewpoint) or not , , sulting in a simple outer contour). The object was presented using parallel projection. Without an attached shadow (shading) the object appeared as an elastic disc horizontally stretching and contracting across the screen of the CRT. With the attached shadow all observers perceived a solid, rotating object in 3D space. A static image of the shaded ellipsoid was still perceived as a 3D object, though its perceived 3D shape differed from that of a dynamic presentation. For example, a static image would appear as a sphere, from viewing the ellipsoid on end.

In another study, Todd (1984) examined depth perception when the depth cues of motion (of a rotating object) and perspective (the use of polar versus parallel projection) presented only congruent information. Five rotating surfaces of differing degrees of curvature (bending towards the observer) were presented on a CRT. These surfaces were depicted in either a polar (i.e., with perspective) or parallel fashion. The surfaces were also either rigid (e.g., a rolling cylinder) or nonrigid (e.g., a cylinder that stretched horizontally as it rolled). They were viewed binocularly. A surface presented with perspective projection was perceived to be more curved than if presented with a parallel projection. However, neither projection (polar or parallel) resulted in increased observer accuracy in judging the amount of curvature present. The rigidity or nonrigidity of a surface had a negligible effect.

Bruno and Cutting (1988) examined depth perception when the depth cues of motion (motion parallax), relative size, height in the visual scene, and occlusion presented only congruent information. Three simple squares, with no

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surface textures, were presented upon a blank background on a vector-plotting display. They represented three parallel panels at equal distances from one another in the depth plane. The depiction of these three panels varied with the application of the following depth cues: relative size, height in the visual scene, occlusion, and motion parallax. The display was viewed binocularly. Observers judged the apparent relative distance between the three panels. Analysis of the data was not done to find the relative importance of one depth cue over another, but to confirm the additivity of depth cues towards the perception of depth. The finding of all cues being relatively strong and noninteracting provided strong evidence for the additivity of depth cues. However, while the presence of more cues did lead to the perception of an increased separation between the panels, it did not increase the certainty of this judgment, which is odd. Variability between observers towards the effectiveness of occlusion (and less so for motion parallax) was noted.

Braunstein (1986) used computer animation to produce motion picture sequences from which velocity gradients could produce one perception of slant, and texture gradients another. He concluded that velocity dominated texture, such that the final perception of slant was influenced twice as much by velocity as by texture.

Cavanagh (1987) used a paradigm identical to that described in Section 3.1.1 involving subjective interpretation of the faces of a Necker cube (Fig. 2.2 left). Relative motion of the faces was placed in conflict with interposition. Observers were divided in their subjective impression of depth, some governed by interposition and some by relative motion.

3.3 Shadows

Rock et al. (1982) examined depth perception when the depth cues of cast

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discern the apparent location of the specular light source from the highlight
is important. This ability depends on the intensity of the light source and
the reflectance qualities of the object's surface.

3.4 Height in the Visual Field

Berbaum et al. (1983) also examined depth perception when the depth cues
of height in the visual field and occlusion presented only congruent
information. Several very simple line drawings were observed monocularly.
These drawings varied in the compellingness of a 3D interpretation of the
object. The amount of depth perceived in a drawing was measured by the
simultaneous use of a stereoscope and a pointer that moved in depth. The most
general result was that the lower part of the visual field appeared closer and
the higher part of the visual field appeared farther away from the observer.
This was also the case when an observer viewed a totally blank field. The
presence of occlusion also increased the perceived depth.

3.5 Texture Gradients

Todd and Akerstrom (1987) examined depth perception when the depth cues
of surface texture pattern and perspective (the use of polar versus parallel
projection) presented only congruent information. Five opaque ellipsoids were
presented on a CRT; all were of a constant width but varied in length (and
therefore depth) along the z-axis. Their surfaces were depicted in either a
polar (i.e., with perspective) or parallel fashion. On the surfaces, the
texture elements were randomly located; the texture elements were either
squares or varied in size and shape. In further experiments, the regular
texture elements were manipulated by controlling their rate of compression as
distance increased, their visible area, their width, and their orientation

(once compressed) relative to the surface of the display (all of which normally covary with compression). The ellipsoids were viewed monocularly.

An ellipsoid presented with perspective (polar projection) was perceived to be slightly more curved than if presented with a parallel projection. The amount of depth perceived did not vary across texture type (regular versus irregular). From the second experiment whose stimuli are depicted in Figure 3.1., the effects of element compression were found to be unimportant, but proper element orientation (i.e., the elements properly aligned on the objects surface) and element width were found to control the perception of depth.

Cutting and Millard (1984) examined depth perception when the depth cue of surface texture followed a perspective gradient (the changing x-axis width of the elementary texture units), a compression gradient (the changing y/x axes ratio), and/or a density gradient (the changing number of texture units per visual angle). All three gradients presented only congruent information. Two static surfaces were portrayed on a vector-plotting display with a vertical dividing line between them. Both surfaces represented either a flat or curved plane whose texture elements were either regular or irregular octagons. The texture elements were randomly placed to avoid the effects of linear perspective. Observers were asked to choose which half of the display appeared more like a flat/curved surface and to assess the strength of this perception relative to the unpreferred side. Perception of the flat surface was controlled 65% by manipulation of the perspective gradient, 28% by the density gradient, and 6% by the compression gradient. In contrast, perception of the curved surface was controlled 96% by manipulation of the compression gradient, and about 2% for both the perspective and density gradients. The use of regular or irregular texture elements had no effect.
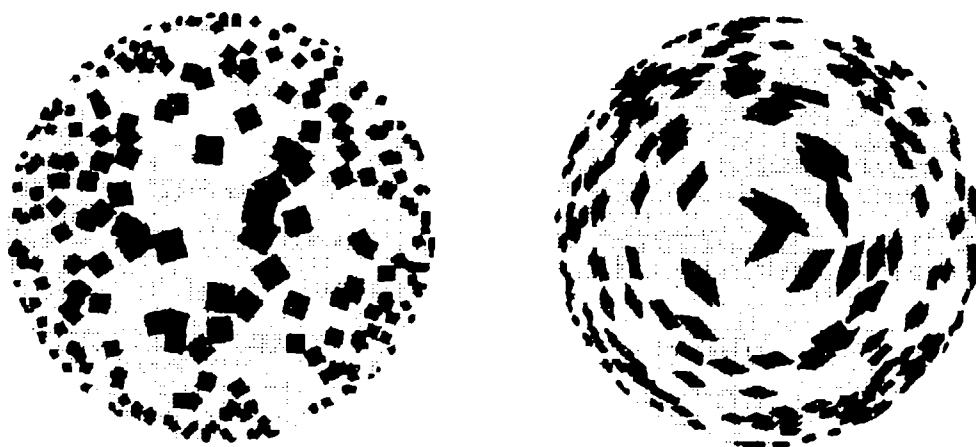
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Figure 3.1. These images represent two ellipsoids pointing out of the page. In the left image, all the texture elements are squares and are increasingly smaller (compressed) along the edge of the image to represent the more distant surface of the ellipsoid as it curves away from the observer. In the right image, the rate of compression is the same as in the left image but the texture units decrease in width and are properly orientated on the surface.

Palmer and Petitt (1977) examined the extent to which collimation of the visual image to optical infinity could augment depth perception induced by textural gradient and linear perspective. Their measure of compellingness was the extent to which subjects are <u>unable</u> to avoid the perception of depth, and thereby report the display size of objects as being what their true size would be, if viewed at a distance, rather than what their retinal image is. If subjects are unable to suppress this depth information, their report of objective display size will grow as perceived distance is increased. The investigators had subjects estimate the display size of images superimposed on a static runway which provided receding cues of linear perspective and textual gradients. Some depth-induced distortion was found with the display viewed at a near image plane. However, when the display was viewed through a collimating lens, projecting it to optical infirity, the distortion was doubled in its magnitude. The authors assumed that collimation does not act as a depth cue itself, but removes a "cue to flatness" (Braunstein, 1976). This removal makes the sense of depth conveyed by other cues that much more compelling.

3.6 <u>Luminance</u> and <u>Brightness</u>

Schwartz and Sperling (1983) examined depth perception when the depth cues of proximity luminance covariance (PLC) and perspective (the use of polar versus parallel projection) presented either congruent or conflicting information. The image of a rotating, luminous, wire cube was presented on a display. The brightness of the individual lines that formed the cube was varied. In the first condition the objectively near side of the cube held the brightest lines while the lines of the far side of the cube were dim; in the second condition this situation was reversed; in the third condition all lines

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of the cube were equally bright. The amount of perspective with which the cube was depicted was varied by presenting either parallel or polar projection. The stimuli employed are shown in Figure 3.2.

Proximity luminance covariance overwhelmingly controlled the perception of depth, with the brighter side of the 3D wire cube perceived as being closest to the observer no matter what degree of perspective was used. In the absence of perspective (parallel projection), PLC determined depth perception in 97.4% of the trials; averaged over all degrees of perspective used, PLC determined depth perception in 90.5% of trials. Perspective by itself affected the depth perceived in a weak and inconsistent manner. A suggestion was made that the PLC effect may not be from luminance per se, but from the effects of contrast between the cube's lines and the background luminance.

3.7 Summary and Conclusions of Cue Combination Studies

The results presented above are summarized in Table 3.1. The table presents various depth cues down the columns and across the rows. Hence, an entry in the table designates a particular study in which the defining row and column cue were either traded against each other in a tradeoff study, or were covaried in a compellingness study. The former are indicated by a single circle, the latter by a double circle. In tradeoff studies, an arrow points in the direction of the dominant cue. In compellingness studies, an arrow (if present) points in the direction of the cue which had greater weight. An "x" indicates a relatively weak effect. An "A" indicates a generally additive relation, a "+x" indicates a positive interaction, such that the presence of one cue amplifies the effect of the other. A "-x" indicates a negative interaction, such that the presence of one cue diminishes or even abolishes the effect of another. Reviewing the data presented in Table 3.1, and
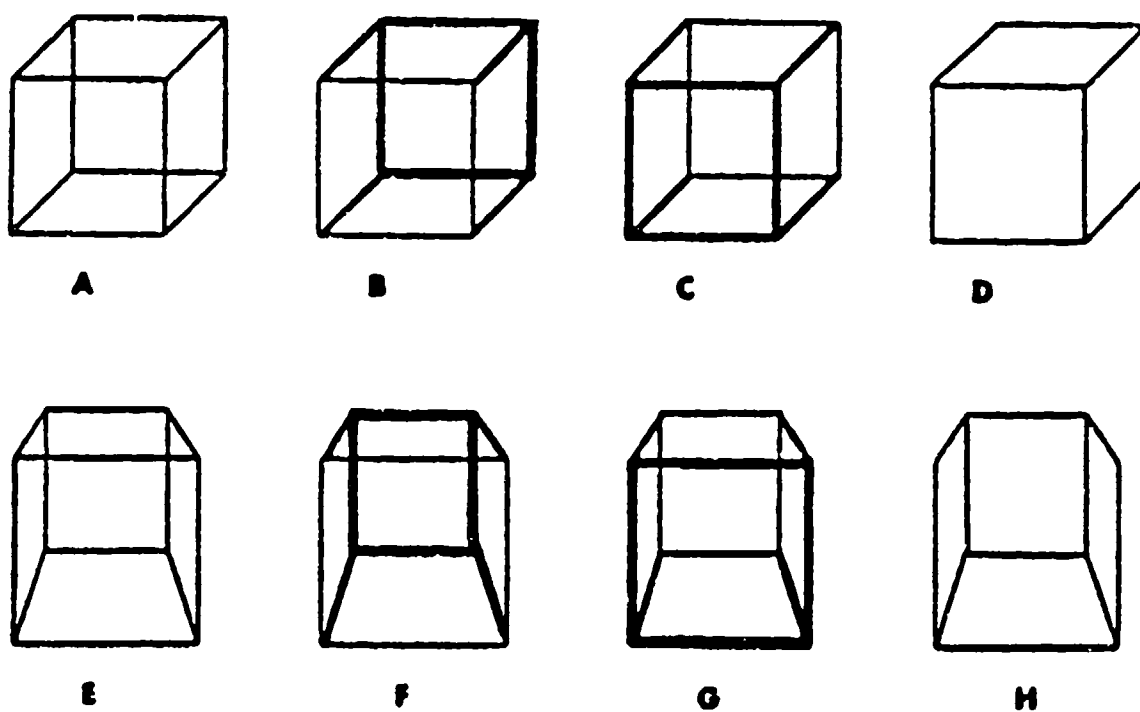
48

Figure 3.2. Various stimuli employed by Schwartz and Sperling (1963).
Showing parallel projection (top) and polar projection (bottom) with PLC in B,
C, F, and G, and surface occlusion in D and H.

Table 3.1   50

A = Additive
-x = Negative Interaction
+x = Positive Interaction
* = Weak Effect

↑
← Conflict

Compellingness

Cue #2:	Stereopsis	Perspective	Motion	Height in the Plane	Familiarity
Cue #1:					
Perspective	↑ Van der Meer *Van der Meer* A *Braunstein* 76 A *Lin* -x		Todd 84		
Motion	*Braunstein & Tittle 89* +x				← *Todd 84*
Height in Plane			*Bruno & Cutting* A		
Relative Size					
Occlusion (Element)	Braunstein et al. 86 ↑ ← Cavanagh 87 ← Tittle et al. 87		*Bruno & Cutting* A	*Berbaum* *et al.* A	
Occlusion (Edge)	← Braunstein ↖ et al. 86		← Cavanagh 87 ↑	Ittelson & ← Kilpatrick	
Motion Gradient	↑ Braunstein *↗ et al. 86				
	↑ Location ← *Prasday* Shape				
PLC	Dosher Sperling & Wurst ↑	Schwartz & ← Sperling			
Shading	Bulthoff & Mallot (a) ↑ Bulthoff & Mallot (b) ↑		*Todd 85* +x ↑	*Rock* *et al.*	**Highlighting** *Berbaum et al.*
Texture		*Todd &* *Akerstrom*	*Braunstein* *68* ↑		
		↑ Slant ← Cutting & Curvature Millard	*Braunstein* ↑ *76* -x		
Collimation		*Palmer* +x *& Pettit*	*Palmer* +x *& Pettit*		

interpreting these in light of the experimental descriptions, allows the following conclusions to be drawn:

(1) Stereopsis is a compelling depth cue and tends to dominate those cues with which it is paired. However, there is no evidence that stereopsis is so totally dominant that its presence eliminates the influence of other cues. In fact, on three occasions stereopsis was dominated by other cues: once weakly and once strongly dominated by edge occlusion, and once dominated by motion in interpreting 3D shape.

(2) Motion is also a dominant cue. Its effects with other cues are either additive, or, if there is an interaction, the form of the interaction is either positive (motion enhances the value of the other cue), or negative (motion diminishes the effect of the other cue, but is not itself diminished by the other cue's presence, i.e., in slant perception and in object recognition).

(3) Occlusion or interposition, although less frequently examined, also shows evidence of being a strong, dominant cue, and becomes more so if the occluding and occluded surfaces are relatively large.

(4) Texture gradient, PLC, and perspective are relatively weaker in the dominance ordering, although they are not unimportant, and do contribute to additive relations in compellingness studies.

(5) Long term experience, as it influences, for example, relative size, appears to be a fairly weak cue. It may be easily dominated by perspective and occlusion, while the assumption of rigidity of objects (an assumption based on long term experience) is also easily violated.

(6) Highlighting is relatively weak, and appears not to be worth the effort and computer power necessary to implement for dynamic displays.

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(7) Generally, an additive model of cue combination with nonequal weights appears to hold up well, with one important exception: the presence of motion appears to violate the model in over half of the cases. This is true in cases when the presence of motion is examined as a cue, or when other cues are examined in a dynamic display (e.g., Kim et al., 1987). Furthermore, Tittle et al. (1988) observed that stereo-deficient viewers of static displays were not stereo deficient when the displays were dynamic. This conclusion suggests the need to be wary about generalizing results from a static display to a dynamic one.

(8) Cue dominance appears to be somewhat task dependent. For example, if 3D shapes of objects are to be recognized in a dynamic environment, stereopsis is less important. If 3D locations of objects are to be interpreted, or if the environment is static, stereopsis becomes more critical. Occlusion, either through hidden lines or hidden surfaces, should always be used in either case.

(9) Absence of cues to flatness can enhance the compellingness of depth cues in an interactive fashion. These may include viewing in a darkened environment, removing display contours, or projecting at optical infinity through collimation.

The preceding conclusions are not offered with complete certainty, and clearly more research is needed on multiple cues. In particular, the conclusions offered above lead to the identification of a number of specific research questions that remain unresolved. For example:

(1) What is the role of immediate past viewing experience on the use of depth cues (Dosher et al., 1986)? Will this experience "lock on" to a perceptual interpretation of near and far that cannot be revised by subsequent viewing, forming a sort of perceptual inertia?

(2) How dynamic must an image be to fully achieve the importanc

influences of motion?

(3) What are the effects of 3D cues on precise check read'.ng ot linear

distances--orthogonal to the line of sight? How are these influenced by field

of view, azimuth, and elevation angles (McGreevy & Ellis, 1986)? Are

illusions of depth also additive with the number of cues?

4.0 3D DISPLAY IMPLEMENTATION

When 3D displays are designed for use in operational settings, a number of specific principles and considerations should be kept in mind, in addition to the specific issue of what cues to incorporate. In this section we review some of these considerations, which impact the actual design of the display. Section 4.1 considers principles for the design of perspective displays, and Section 4.2 addresses those considerations that are specific to displays using observer-centered cues. This second section, of necessity, focuses heavily on the existing technology for creating stereo or virtual images.

4.1 Perspective Display Implementation

4.1.1 Geometry of perspective viewing. When perspective geometry is employed to represent specific locations of objects and landmarks in space, a series of considerations must be addressed (McGreevy & Ellis, 1986; McGreevy, Ratzlaff, & Ellis, 1986; Ellis & Grunwald, 1989; Ellis, 1989). Many of these are best understood in the context of a picture of the geometric relations involved in such a display, as illustrated in Figure 4.1. The figure depicts an eye viewing a display frame of an outside scene. The geometry of the scene is depicted from a top-down orientation. Two objects, an "x" and an "o" are depicted in the outside scene, and these are also presented on the display image plane. Five terms are critical to understanding the geometry of the perspective viewing in Figure 4.1.

(1) The visual angle (VA) of the screen is the angle subtended by the display screen as it is observed by the viewer.

(2) The viewing distance (VD) is the distance of the eyes from the display screen. Hence, VA is determined by display screen size (DS) and VD.
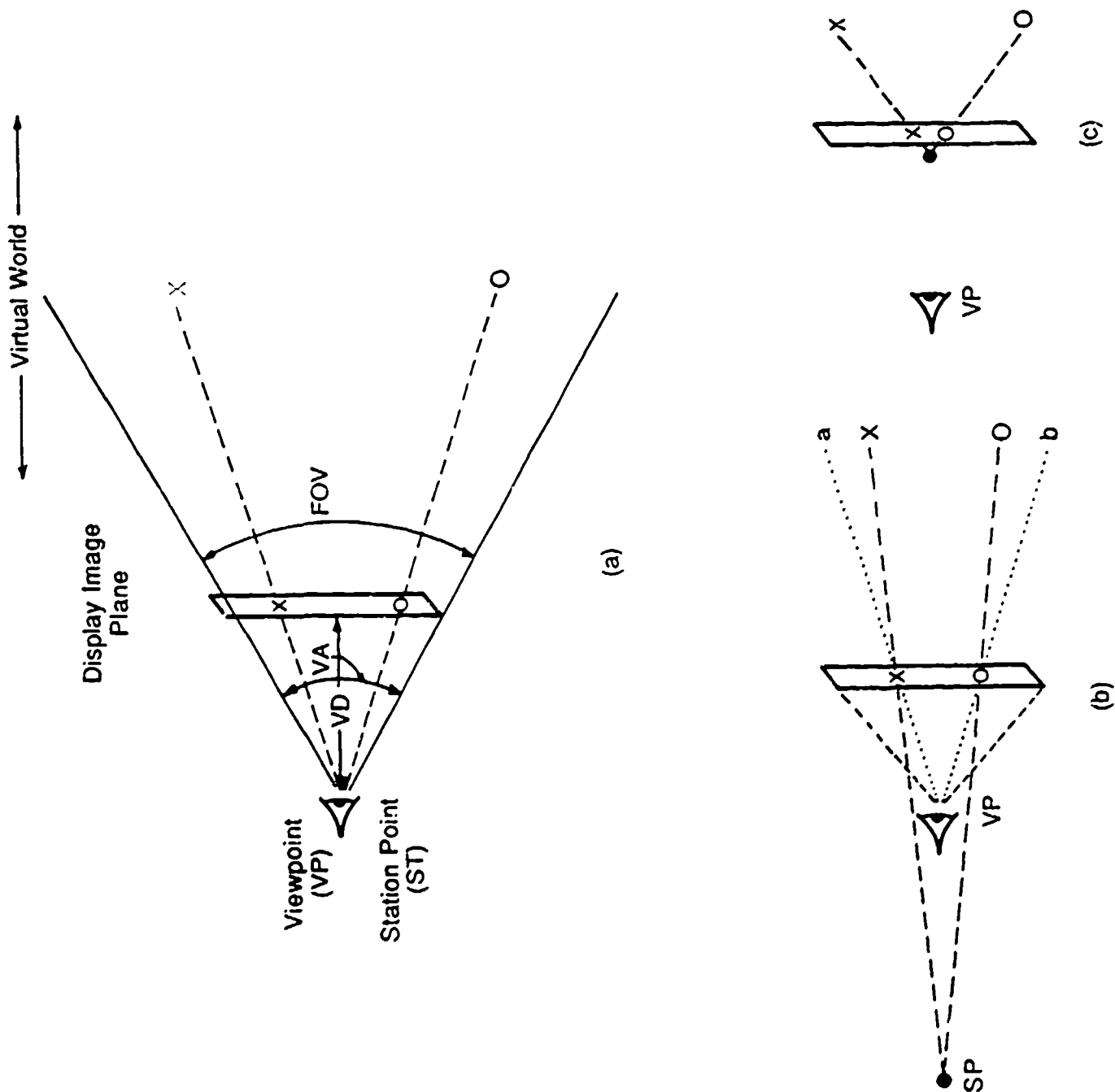
Figure 4.1. Geometric relations in perspective display viewing (a) optimally positioned viewpoint, (b) magnified display, (c) minified display. VD = Viewing distance. VA = Visual angle of the display. FOV = Field of view of the display. X and O are objects in the virtual world, whose images are depicted on the display.

'3) The display field of view (FOV) is the angle depicted by the display image from a hypothetical point where all light rays would converge. In Figure 4.1, this point happens to be precisely at the eye position or view point.

(4) This point of convergence is defined as the station point or center of projection. At the VD where the view point and station point are identical, the visual angle and the FOV will be identical; hence, objects in the real world--and their depiction on the display--will be aligned. This is the case in Figure 4.1(a). Naturally, for a given viewing distance this correspondence will not always be observed. Figure 4.1(b) shows a situation in which the correspondence is violated because the display is magnified, relative to the viewing distance--as if seen through a telephoto lens. Here the station point would be quite far from the display. Points a and b represent where the observer would perceive objects x and o to be. Figure 4.1(c) shows a minified display like a wide-angle lens, imposing the station point at a very small VD.

When a 3D perspective display is designed to present an outside-in or "God's Eye" perspective, two additional parameters must be assumed as shown in Figure 4.2. The elevation viewing angle is the angle from which the display "camera" looks down upon (or up to) the highlighted object in a display. In the cockpit display of traffic information, used to illustrate this point in Figure 4.2, this object is the circled plane in the center of the display, referred to as "own ship." The azimuth viewing angle is the angle from which the object is viewed, relative to a canonical "straight ahead" orientation. In Figure 4.2, this azimuth angle is about 8° to the right.

4.1.2 Distortions of perspective viewing. It is apparent that these various factors considerably complicate the design of perspective displays,
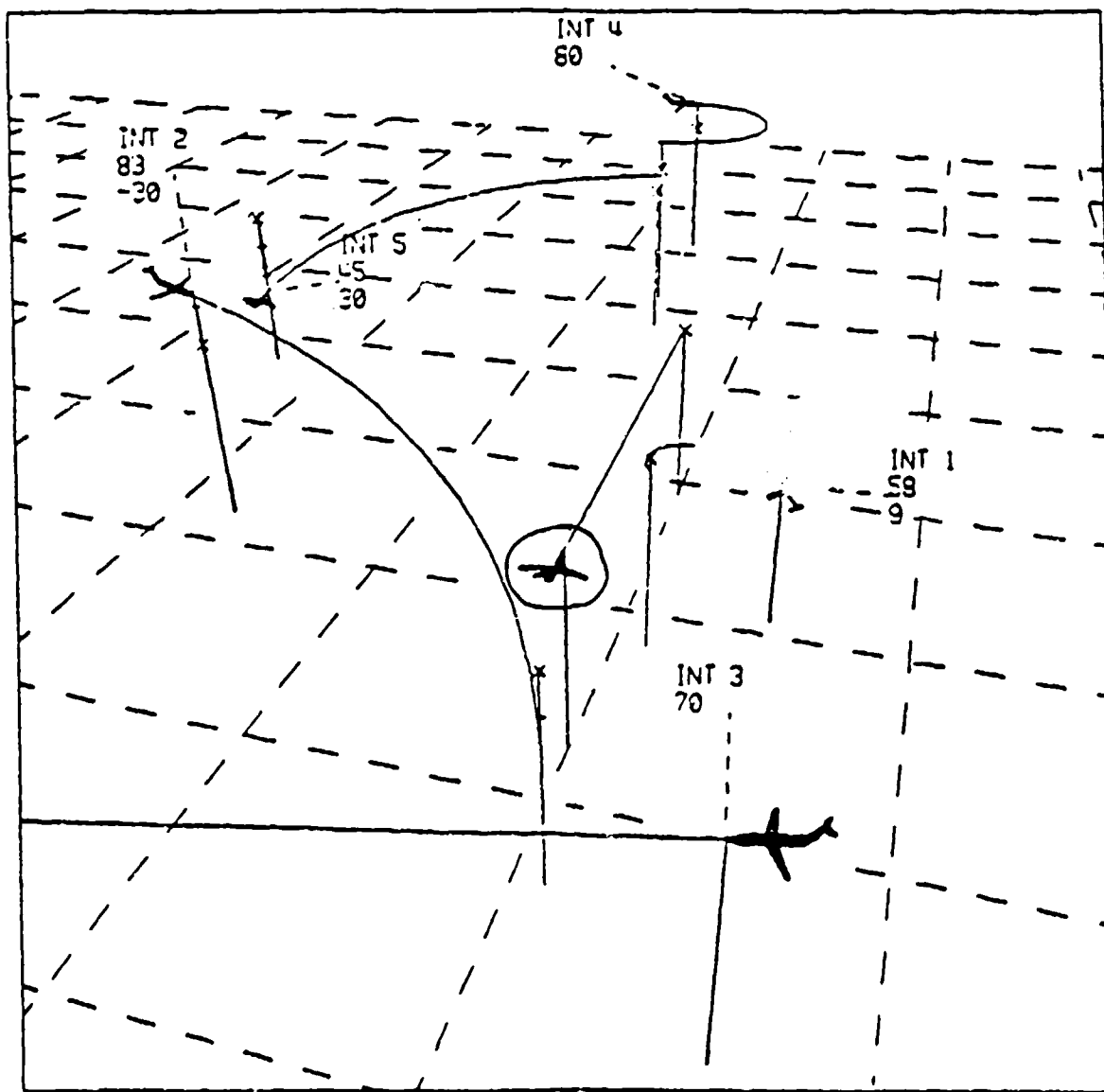
Figure 4.2. Perspective display viewing. The display illustrates an elevation viewing angle of 30° (from above), and an azimuth viewing angle of 8° (to the right) (from Ellis et al., 1987).

and suggest the need for principles which optimize the setting of all parameters. Some empirical evidence does however exist to guide the parameter specification. Much of this evidence is in the form of measured distortions perceived as the scene is viewed from particular perspectives. For example, Roscoe, Corl, and Jensen (1981) point out that perspective displays of this sort are perceptually "minified." That is, even with the viewpoint at the station point as shown in Figure 4.1(a), objects are perceived as closer together (or smaller) than they really are. Hence, using the size-distance invariance equation, the distance of those objects from the observer is seen as greater than it really is. In aviation, this could lead to faster than desirable approaches to a runway. Roscoe et al. conclude that a display magnification of approximately 1.3 is necessary to compensate for this perceptual minification. They also point out that for aviation applications, the FOV should be sufficiently wide (around 40°) so that the forward path of an aircraft can be viewed even as the aircraft is "crabbed" 20° to one side or the other into a crosswind.

A set of biases and distortions associated with viewing world-referenced perspective displays, such as the air traffic controller display shown in Figure 4.2, have been identified and modeled in a program of research carried out by Ellis, McGreevy, and their colleagues at NASA Ames Research Center (Ellis, 1989; Ellis & Grunwald, 1989; McGreevy, Ratzlaff, & Ellis, 1986; McGreevy & Ellis, 1986; Ellis, Smith, & Hacisalihzade, 1989; Ellis, McGreevy, & Hitchcock, 1984; 1987). Their empirical studies have modeled the kinds of biases an observer would make in trying to estimate the bearing and elevation that an "intruder" aircraft would show relative to own-ship in a display like Figure 4.2. The schematic display used in their research is shown in Figure 4.3.
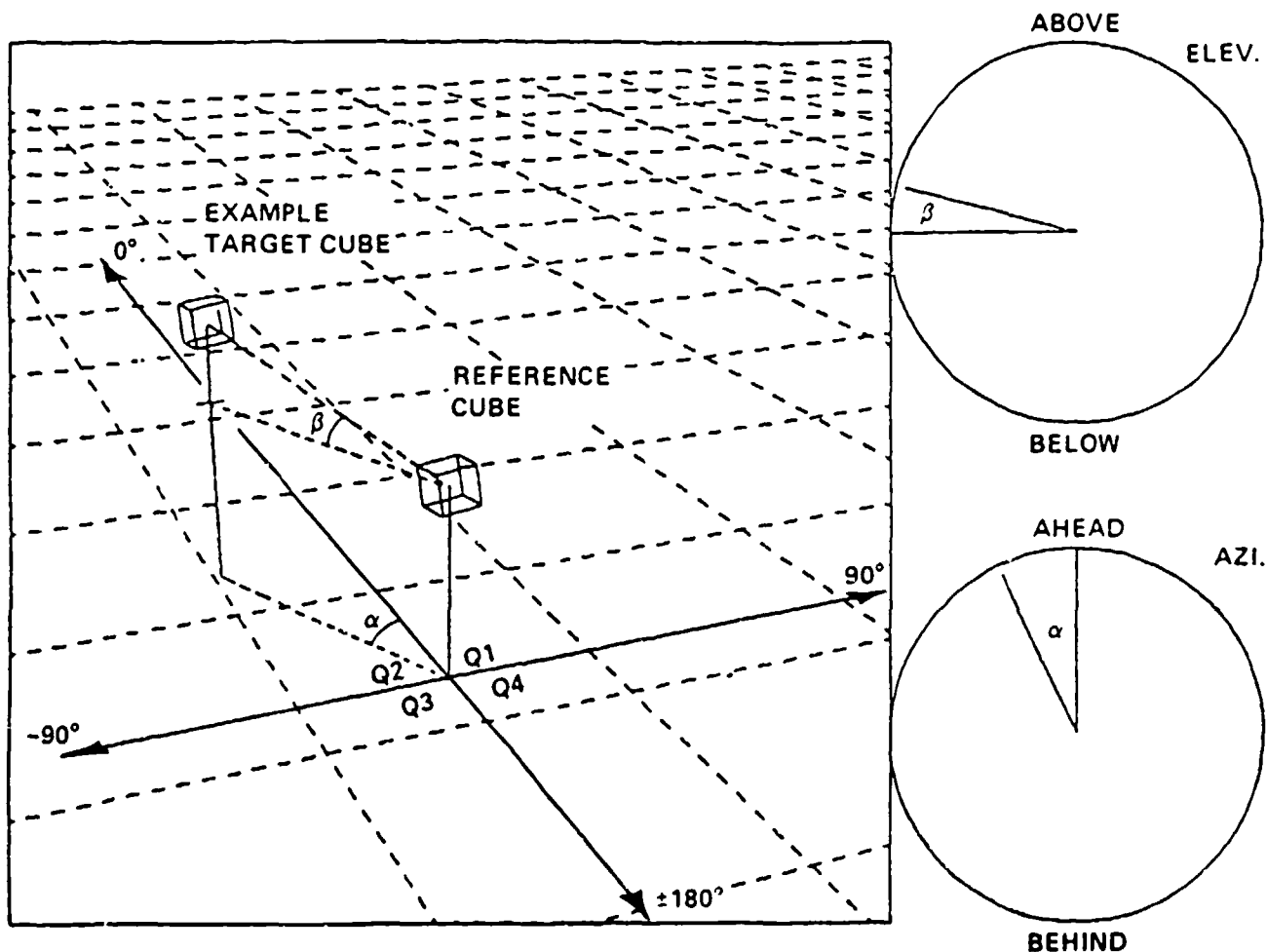
Figure 4.3. Perspective viewing display used by Ellis and his colleagues. Subject is asked to estimate the azimuth (α) and elevation angle (β) of the target cube from the reference cube. This typifies the kinds of judgment that an air traffic controller might make regarding the relative positioning of two aircraft.

Observers indicate their response by adjusting the two angular indicators shown beside the display.

Ellis and his colleagues have identified two general forms of error that are shown when people make these visual estimations from perspective displays.

(1) Estimation of elevation angle tends to be perceptually exaggerated. This bias toward overestimation of positive angles (underestimation of negative) is greatest at $\pm$ 30°. The bias is also modified by the display FOV, and is smallest with larger FOVs (e.g., 120°).

(2) Azimuth estimations are biased in a direction towards the angle formed on the 2D image plane. That is, the relative bearing is perceived closer to the bearing parallel to the image plane, than is the veridical. This latter form of bias is modeled to be the result of two perceptual effects:

> (i) the 2D-projection effect is the result of an "averaging" process, whereby the estimated azimuth angle is the average of its geometrical perspective angle, and the angle projected onto the image plane; and

> (ii) the virtual space effect results from the viewer's relatively automatic assumption that the view point is located at the station point. The observer then hypothesizes the virtual space that would be required to produce the given displayed image. Thus, for example, in Figure 4.1(b) the observer would be biased to assume that the "x" and "o" in the world are closer to the positions marked "a" and "b," and extended from the dotted line.

The magnitude of both of these effects combines interactively with VA, VD, FOV, viewing azimuth, and elevation angles, along with the actual angle

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and elevation between the target objects to form a fairly complex series set of effects, some of which are shown in Figure 4.4 (McGreevy et al., 1986). The figure presents different combinations of VD and FOV, and shows how positions within this two-dimensional parameter space influence the two sources of error.

Finally, Ellis, Smith, and Hacisalihzade (1989) have noted that the kinds of estimations people make via world-referenced coordinates, like adjusting the angles in Figure 4.3, are qualitatively different from those shown by egocentric judgments (pointing or looking).

4.1.3 Corrective measures. Equally important to the identification of these effects are the prescriptions that can be made to minimize these and other biases, which will distort the perceived location of objects. These prescriptions may be placed into three general categories: parameter specifications, geometric enhancements, and symbolic enhancements (Ellis, 1989; Ellis & Grunwald, 1989).

Parameter specifications. The schematic representation in Figure 4.4 reveals that minimum biases will occur with a large FOV, matched by a large viewing angle. Biases in general tend to be smaller when the VA and FOV are matched. Furthermore, as might be expected, higher-elevation viewing angles will reduce the magnitude of azimuth errors (in the extreme, a 90° viewing angle is a top-down view, equivalent to a 2D map display, and will have near perfect azimuth angle judgments). In optimizing their perspective display for a cockpit display of traffic information, Ellis and his colleagues have chosen an elevation angle of 30° and an azimuth angle of 8° off center from behind own-ship. This choice is based upon pilot opinion.

Subsequent research by Kim et al. (1987), using the 3D tracking paradigm described in Section 3.1, revealed that tracking performance was nearly
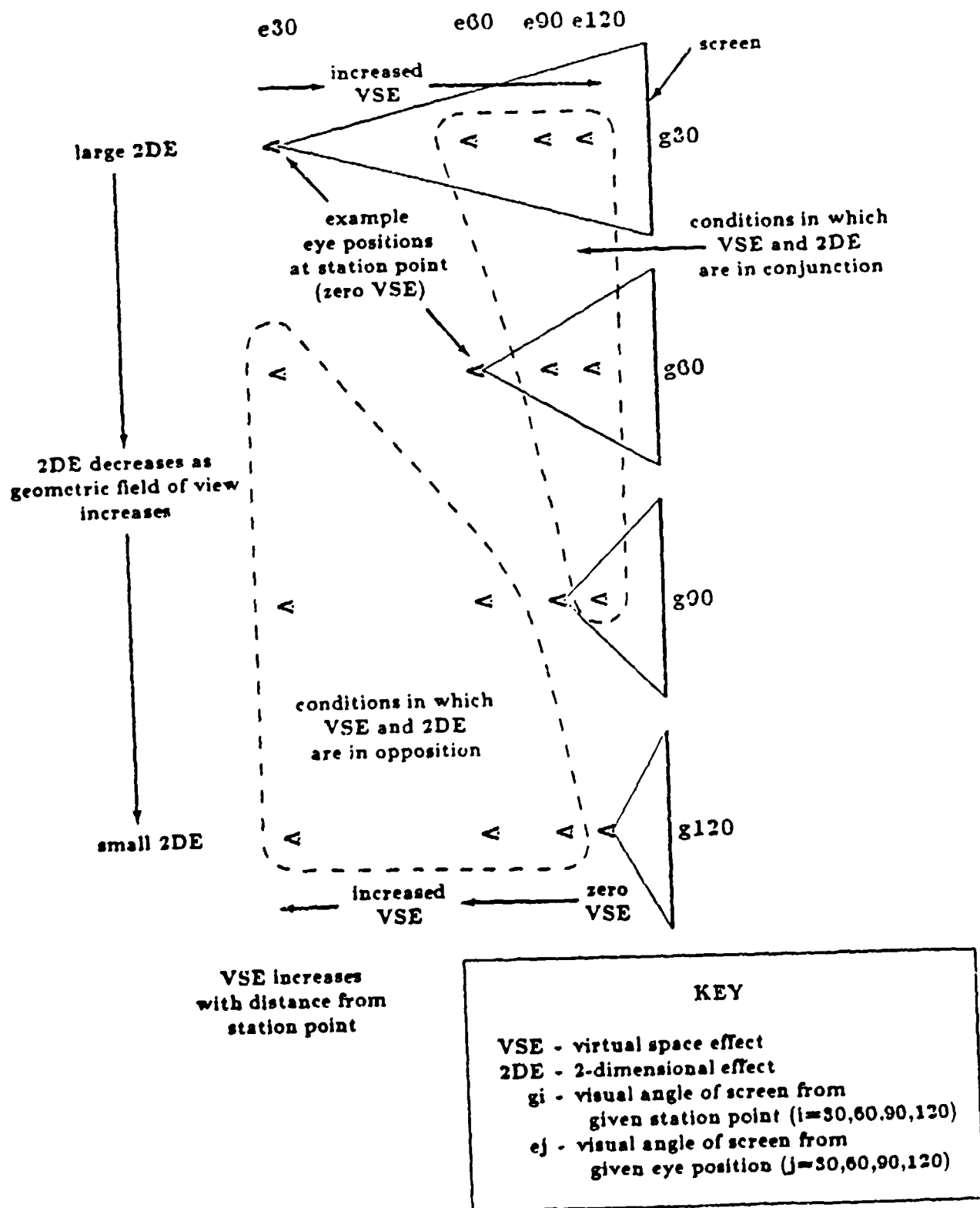
61

Figure 4.4. Presents viewing conditions used by McGreevy et al. (1986), showing how these affect the two forms of bias produced by the virtual space effect and the two-dimensional effect.

equivalent at elevations between 30° and 60°, but fell off with more extreme angles. Tracking performance was essentially equivalent across azimuth angles from 0 to 40°.

In a slightly different paradigm, Yeh and Silverstein (in preparation) asked subjects to make judgments of altitude and distance from the viewpoint of perspectively viewed aircraft symbols. Changing elevation angle produced a tradeoff in the quality of performance between the two dimensions of judgment (altitude and distance). Altitude judgments became worse, and distance judgments improved at the higher elevation angle (45° vs. 15°). However, tradeoff was such that the combined performance on both dimensions was better at 15° than 45°.

Geometric enhancements. These include actual biases or distortions incorporated into a perspective display, which may compensate for the observed perceptual biases. The proposal by Roscoe, Corl, and Jensen (1981) that there should be a 1.3 magnification factor in perspective viewing displays is one such example. Another is the characteristic that the vertical dimension is routinely amplified relative to the horizontal for ATC displays (Ellis, McGreevy, & Hitchcock, 1987). A third geometric enhancement is to introduce a nonlinear scaling of object size with distance, to ensure that displayed objects do not become vanishingly small at extreme distances.

Symbolic enhancements. These represent artificial elements introduced into the display that are not part of the virtual world, but serve to disambiguate the display, or enhance its perceptibility. Most effective here are the "posts" upon which each aircraft in Figure 4.2 is mounted. When these are coupled with a grid surface to which the post is attached, and are marked with an "x" indicating own-ship's altitude, then the true altitude and location of the intruder aircraft becomes unambiguous. Another symbolic

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enhancement developed by Ellis, McGreevy, and Hitchcock (1987) and shown in
Figure 4.2 is the second post, connected to the ground from a point on the
vector predicting the aircraft's flight path. This feature unambiguously
specifies heading. While this feature does not eliminate the azimuth
estimation error described above (Figure 4.4), it does eliminate the tendency
of this error to increase as the viewing perspective elevation angle
decreases from the top-down toward the horizontal (Ellis & Grunwald, 1989).

Numerous other symbolic enhancements can be designed into such displays,
including the presentation of digital readouts, color, or brightness coding.
At this point, however, the display designer must be very cautious that the
inclusion of extra objects does not create sufficient clutter to neutralize
the ease of interpretation which led to the choice of 3D representation in the
first place. Wickens, Haskell, and Harte (1989a,b) discuss ways in which
symbolic enhancements can be integrated into objects that are already part of
the display, thereby minimizing the addition of display clutter.

4.2 Observer-centered Cue Implementation

Four major classes of techniques have been used to convey a sense of
depth through nonperspective, observer-centered cues. These involve
holographic displays, multiplanar displays, binocular displays, and active
parallax displays. Displays within each of these categories in turn can be
described in terms of whether special viewing glasses must be worn. If the
glasses are not worn, then the displays are described as auto stereo displays.
Holographic and multiplanar displays are autostereoscopic. Binocular displays
may or may not be.

4.2.1. Holographic displays use a technique of optical interference
between images projected from two different light sources to create a 3D image

(Hodges, Love, & McAllister, 1987; Okoshi, 1980). While the image is "virtual" and exists in 3D space, it still leads to some distortion in relative distance judgment (Frey & Frey, 1985). In addition, there are numerous technological difficulties in generating real time holography, which can be dynamically updated (Hopper, 1986). Also, holographic displays are, by design, limited in the field of view, and the display will change with the angle at which it is viewed (Williams & Garcia, 1989a,b). Good technical reviews of holographic display technology may be found in Okoshi (1980) and Hopper (1986).

4.2.2 **Multiplanar displays**. Multiplanar displays are typically created through a system of rotating or vibrating mirrors (Williams & Garcia, 1989a,b; Huggins & Getty, 1982). Such displays are also referred to as "volume visualization displays" because they can create a virtual volume within which a 3D image can be constructed. A current version marketed by Genisco creates a maximum volume of 25 cm^3, with a 30-Hz refresh rate. A larger version semi-spherical volume with a base of 3 ft. has been developed by Williams and Garcia (1989a,b). Two envisioned examples are shown in Figure 4.5. The advantages of this display are its virtuality, and the fact that multiple users can walk around and inspect the display. Its costs are related to the early state of development of the technology (and the resulting financial costs), and to the fact that it is not appropriate for use in creating solid objects, area shading, and filling (Williams & Garcia, 1989a,b). Huggins and Getty (1982, 1984) have used the volume visualization display to examine various aspects of 3D compatibility in manipulating and orienting 3D objects.

4.2.3 **Stereoscopic displays**. In contrast to holography and multiplanar displays, stereoscopic displays do not attempt to recreate a "virtual" 3D environment, but as noted in Section 2.7.2, simulate depth by presenting two
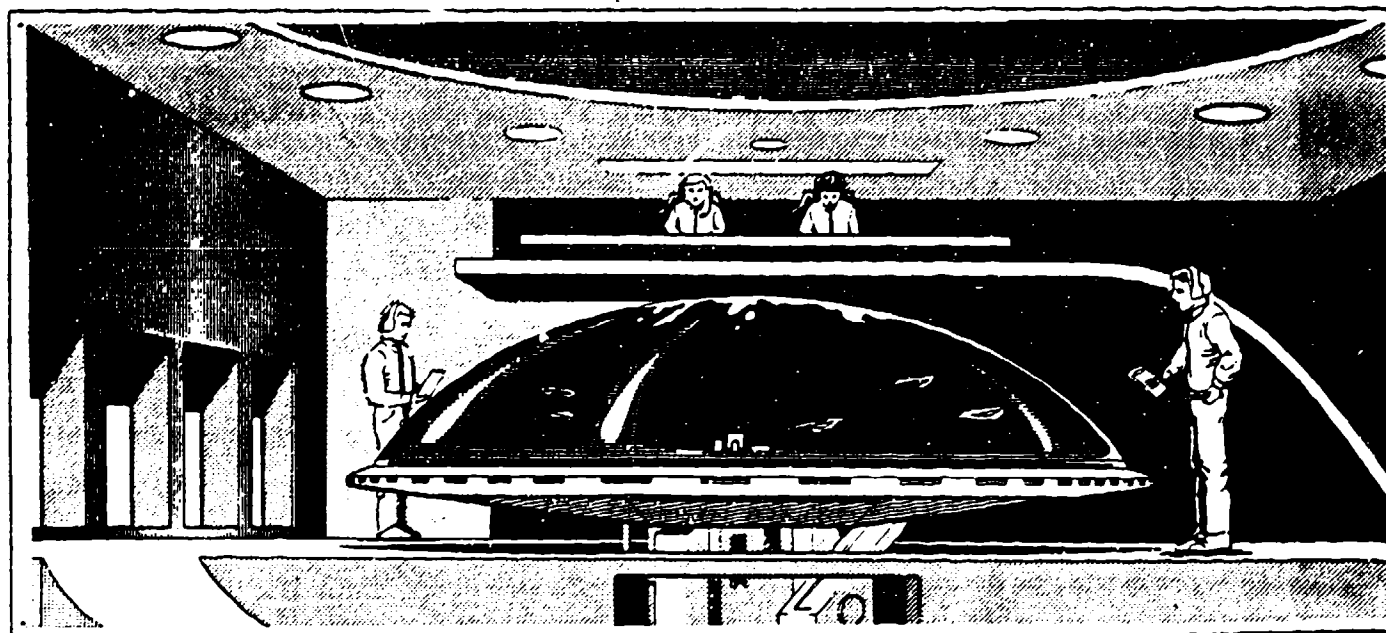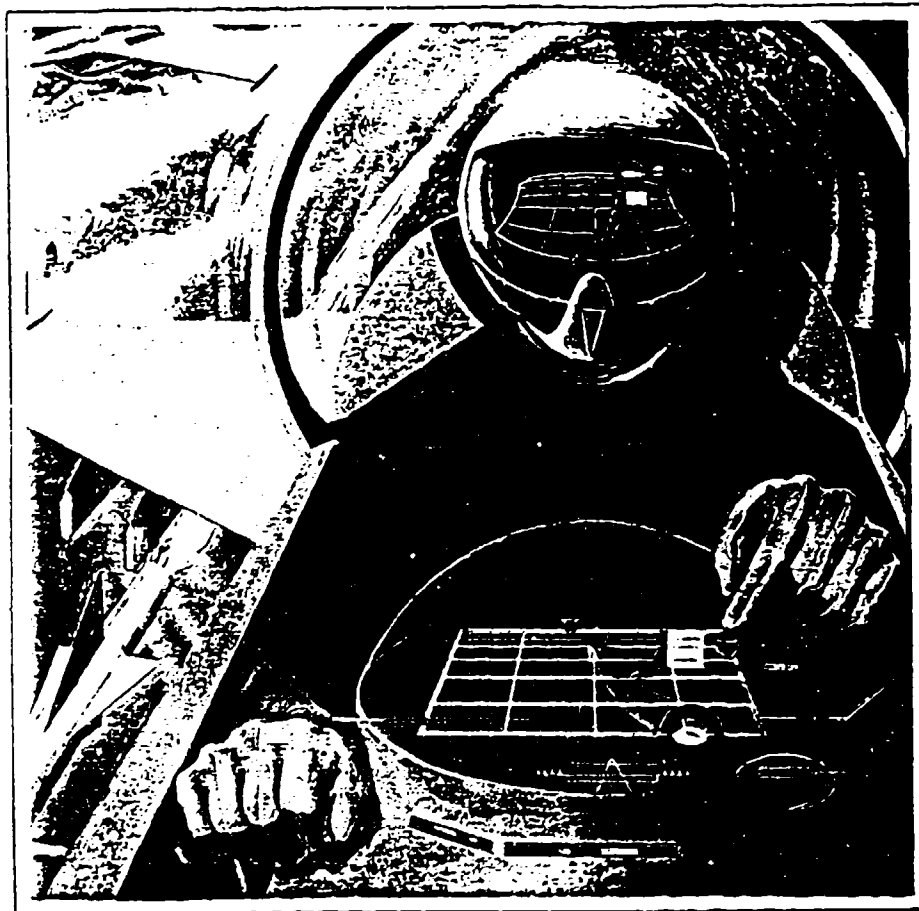
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Figure 4.5. Two possible examples of applications of multiplanar displays
(Williams & Garcia, 1989b).

disparate images, one typically presented to each eye, with each image depicting the disparate view that would be obtained if the virtual image were viewed. Stereoscopic displays may be categorized in terms of whether the two images are viewed simultaneously or in alternation. These are described as time-parallel and time-multiplexed displays respectively (Hodges & McAllister, 1985; Johnson, 1989).

Time parallel displays are typically created by presenting the two disparate images in different wavelengths of light and then using different filters on each lens of a pair of glasses to present a different image to each eye. This technique is used in what is known as an anaglyph display, and was commonly used in 3D movies during the 1950's. The classic stereoscopic display employed in the stereoscope or view master is also time-parallel, and uses optical techniques to present the two images.

Techniques for using time-parallel displays with slide projectors for group presentations are described by Wixson (1989). Fuller and Phillips (1989) discuss the use of time parallel stereo display for aerial refueling or remote control of off-road vehicles, where stereo depth judgments must be extremely precise. 3D Image Tek Corporation of Glendale, California, is one manufacturer of such a system. An important issue with regard to time-parallel displays is the viewing separation and degree of convergence of the two camera lenses. This is typically set at the separation of the eyes, around 2 1/2". However, some advantage is gained if the separation can be increased for viewing at great distances, when the amount of natural disparity is reduced.

Another issue with regard to stereo camera positioning concerns whether the camera configurations should be parallel or converging. For a number of reasons, converging configurations are superior for close-in work such as that

involved in remote manipulation or teleoperation (Diner & von Sydow, 1988).
There also appears to be a performance tradeoff caused by the amount of
convergence of camera angle. Large angles, with a wider separation than the
two eyes, generating "hyperstereopsis" or "super stereo," produce very precise
depth resolution, but at the expense of some 3D distortion of objects'
location in space. Smaller angles reduce distortion, but also allow less
resolution. Diner and von Sydow (1988) identify certain compromise viewing
conditions that can optimize the position on the tradeoff for close-in viewing
used in teleoperation.

Time-multiplexed displays are implemented by presenting the two
disparate images at a rapid rate of alternation, typically around 30 Hz. To
ensure that each image is viewed only by the appropriate eye, the viewing is
typically accomplished through glasses in which each lens is polarized to a
different orientation. A rapid shutter system is synchronized with the
display generator, so that when the left eye image is displayed, polarized
light will only pass through the left lens, while opposite polarization aligns
the right eye image and lens on the alternate cycle. This alternation may be
accomplished by driving the lens of polarized glasses themselves, through PLZT
or Liquid Crystal Shutter Technology (LCS) (Bridges & Reising, 1987).
Alternatively, LCS technology can be implemented on an overlay on the front of
the CRT display screen. These two approaches are sometimes described as
"active" and "passive" stereoscopic systems. The large LCD display required
of passive systems has a considerably greater cost (around $6,000 for a 19"
plate) than the smaller glasses of the active system, which may be available
for as low as $300.00 (Johnson, 1989).

Binocular time multiplexed displays are currently the most frequently
used stereoscopic display technology because of their relatively high

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compatibility with CRT-based image generating devices marketed by Tektronix Corporation of Portland, Oregon, and Stereographic Corporation of San Rafael, California. While their degree of effectiveness in supporting task performance will be discussed in Section 5, the costs of these forms of stereographic displays are as follows:

(1) Physical constraints. Both LCS and PLZT technology are more constraining when the viewer must wear glasses whose lenses are synchronized to the display, because of the wiring necessary and the greater expense and vulnerability of the glasses. PLZT also requires high voltages in the glasses. Because LCS technology can be implemented on a wide screen display overlay, the alternation or shuttering mechanism can be imposed at the surfaces of the display, rather than in the glasses, which then only need to be equipped with two nonshuttered polarized lenses. This is a clear advantage.

(2) Viewing perspective. Alternating frame technologies produce a distorted image as the viewing perspective changes, and the 3D imaging is lost if the head is tilted.

(3) Image intensity. The use of polarization, by definition, eliminates much of the light energy, and images become less intense.

(4) Spatial resolution. As typically implemented on a raster display, left and right eye images are generated on alternating raster lines. This feature degrades the vertical resolution of the display. An alternative is to generate each eye image on all raster lines. However, this technique will halve the frame rate to 30 Hz and may produce perceptual flicker (Johnson, 1989).

(5) Ghosting. The compellingness of the alternating-frame stereoscopic view depends upon the extent to which the off-cycle image does not stimulate

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the retina. The combined effects of slow CRT phosphor decay, and retinal sensitivity to the persisting image can lead to a perception in which the residual image of the off-cycle display is viewed by the other eye. This produces a "ghost" double image. Ghosting may be reduced or eliminated by the appropriate choice of display hue. Red or orange hues present minimal ghosting compared to white (Yeh & Silverstein, 1989). However, the display luminance is greatly reduced in this case.

(6) Resolution and fusion. Large amounts of disparity cannot be adequately fused, and a double image becomes quite apparent. The range of disparity over which fusion is possible is referred to as Panum's fusion area. Within a Tektronix SGS 430 display, these limits are approximately 21 minutes of arc for crossed disparity, and 24 minutes for uncrossed (Yeh & Silverstein, 1989). While roughly 10% of the population is unable to fuse static stereoscopic images, this limit appears less constraining for dynamic images (Tittle, Rouse, & Braunstein, 1988).

In addition to LCS and PLZT technology, a third alternating-pairs approach to 3D imaging uses vertical, rather than horizontal disparity (Jones et al., 1984). Two images, depicted from about $1-1.5^{\circ}$ visual angle disparity are alternatively presented. Effective stereo perception is obtained at alternation rates between 4 and 30 Hz. This technique has two distinct advantages over the alternate frames binocular stereoscopic techniques described above:

(1) Because both eyes see the same image, there is no need for alternating frames and polarized or shuttered glasses. It is a binocular autostereoscopic display.

(2) The absence of glasses allows stereo to be perceived as the head is rotated.

The primary cost of this technique is related to its poorer image quality, and the fact that the display produces a "rocking" sensation when viewed (Hodges & McAllister, 1985).

4.2.4 Active parallax displays. Active parallax displays capitalize on the compelling sense of depth created by relative motion. Such a display, designed by Suetens et al. (1988) uses physical movement of the head, as recorded by head position sensors to drive the relative placement of objects on the image screen, thereby presenting the same sense of motion parallax that would be created if a true 3D scene were examined from different viewpoints. Suetens et al., describing the applications of this technique to medical imaging, have coupled it with stereo viewing providing what they describe as a compelling sense of depth.

However, one drawback acknowledged by the authors is that active parallax imposes a need for rapid display updating, since this updating must be directly tied to head movement. Hence, unless images are relatively simple, the technique becomes computationally quite intensive. As a result, it is restricted to wire frame figures. The authors note in their rendering that hidden line algorithms are also sacrificed. However, the combined compellingness of stereopsis and motion apparently resolves any ambiguity, although no data are cited.

5.0 DISPLAY APPLICATIONS

The discussion in this section concerning the implementation of 3D technology in displays takes a different perspective from that presented in Sections 2 and 3, where the emphasis was on the psychological principles underlying the perception of depth. The display designer is less concerned about the psychology of depth perception, per se, than about the need to present information in an interpretable fashion, capitalizing on depth perception where it is useful. In the following sections we consider a variety of applications which have employed a display representation of depth either to represent depth itself, or to simulate another, nondistance, dimension.

In addition to the separate categories of application (e.g., aircraft display, graphic data depiction), the conclusions in the report studied are grouped according to the following four experimental or review orientations: (1) those studies that have compared a 3D representation to a 2D counterpart, (2) those studies that have examined different facets of 3D display representation (e.g., varied the number of cues, or examined the presence of distortions), (3) those studies that have implemented and evaluated 3D display technology, and (4) those papers that have proposed a 3D display technology or application. Since the emphasis of the current report is on empirical data, studies in the latter category will be included only to the extent that they have not yet been followed by empirical evaluations. Two other points are relevant to the following review: (1) Some applications may fit within more than one category, and for reference purposes are discussed in both. (2) Given the special status of stereoscopic displays as an emerging display technology, these displays will be given prominence in some of the following sections, where recent developments have been more extensive.

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5.1 Aircraft Cockpit Applications

Because of the six degrees of freedom in Euclidian space which characterize flight (translation in x, y, and z; rotation in pitch, roll, and yaw), and because of the apparent difficulty in integrating this information from traditional 2D display representations of the cockpit instrument panel, flight path guidance displays have provided a natural domain for development and application of 3D display technology, with major research programs found at Wright-Patterson AFB (AFFTWAL and the Air Force Aerospace Medical Research Laboratory Human Engineering Group), Naval Air Development Center, and NASA Langley. To provide a context for the following discussion, Figure 5.1 presents a generic prototype of such a display. Variations of this prototype have served in most of the studies discussed below.

Studies reported in the following section have been driven heavily by three forces: (1) The emergence of the microwave landing system (MLS), allowing curved approaches to airports (Remer & Billmann, 1987), has highlighted the concern for flight displays that support precise situation awareness of the position along the flight path through a perspective "highway in the sky." (2) 3D display technology has also enabled the creation of displays that provide the combat pilot with a greater degree of tactical awareness (Boff & Calhoun, 1983). (3) Technical developments in visual flight simulation have continued to address the best ways of making the pilot aware of his orientation and altitude over the ground, for both civilian and military flight.

5.1.1 2D versus 3D comparison. Surprisingly few studies have actually been undertaken to provide an objective comparison of 3D and 2D representations of the same information in flight. One such study, carried out by Grunwald, Robertson, and Hatfield (1981) examined a 3D "highway in the
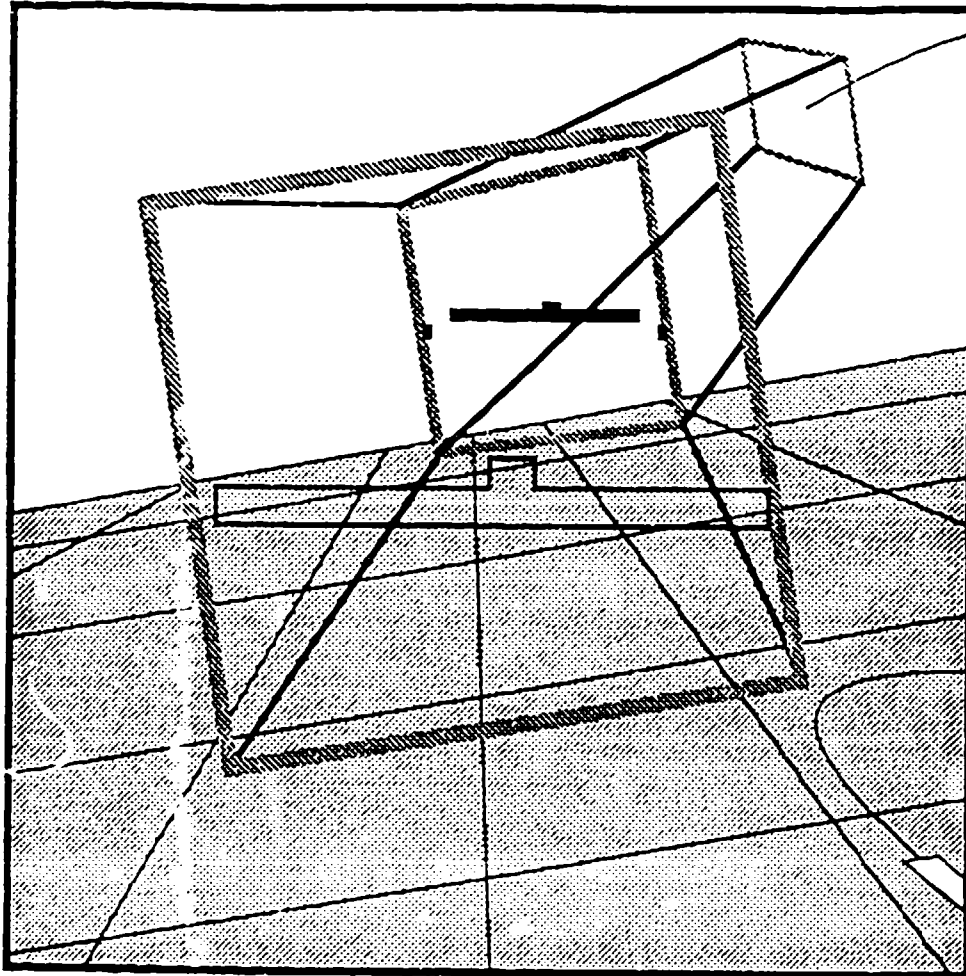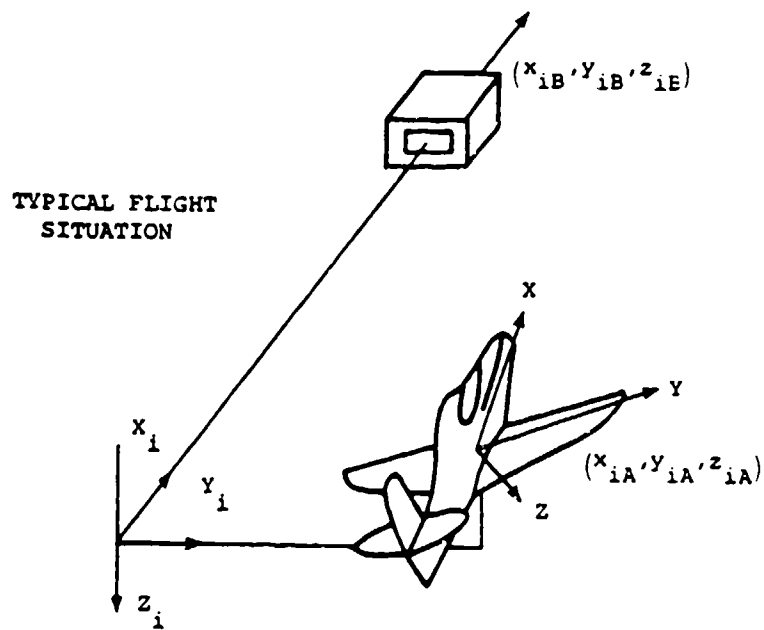
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Figure 5.1. Example of perspective flight path display (Wickens, Haskell, & Harte, 1989a,b). The predicted aircraft position is shown as the smaller black aircraft symbol. The desired flight path tunnel recedes into the distance.

sky" display, with preview and prediction, designed for helicopter approaches. A prototype using textural gradient and convergence to convey flight path depth, was compared with a prototype that presented the same predictive and preview information, without the supplementary depth cues. Although performance on the former display was superior, the difference was not large, and emerged only at the longest predictive interval (1000 feet). Data were reported for only one subject. Another study by Wickens, Andre, and Moorman (in preparation) contrasted a 3-view planar display with an outside-in perspective display to support navigation across a simulated airspace. The 3-view display presented a forward looking attitude display indicator, a side view vertical situation indicator, and a top view map. Performance of nonpilot subjects was superior with the plan view displays, because of difficulties that subjects had resolving depth ambiguities along the line-of-sight, when using the perspective display.
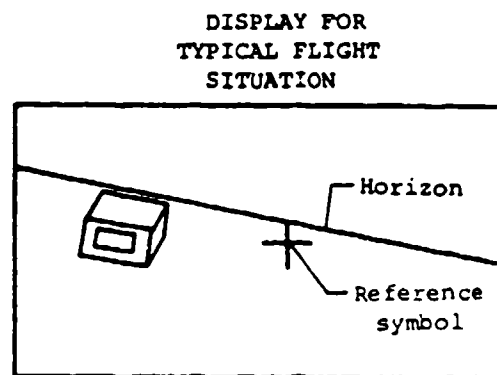
5.1.2 **3D predictor-preview implementation**. In contrast to the weak empirical evidence described above for an advantage of 3D over 2D when both display formats provide equivalent information, there is strong evidence that a flight path display incorporating 3D prediction and preview is superior to one without such information. Studies by both Reising, Barthelemy, and Hartsock (1989) and Wickens, Haskell, and Harte (1989a,b) have drawn such a conclusion with experiments using a relatively large sample of subjects. It is, of course, impossible to determine if the advantages offered by the 3D predictor and preview information, since conditions were not examined in which the latter information was offered in 2D form. Both studies, however, offered further conclusions about the implementation of 3D technology to be discussed below.

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5.1.3 <u>3D implementation of flight displays</u>. Grunwald (1984) provides a detailed discussion of the implementation of a 3D perspective display for aircraft landing approaches, implemented at NASA Langley Research Center, and describes an evaluation based on four extensively trained nonpilots, and two pilots. The display provides a receding series of boxes, forming a flight path tunnel in the sky. Two aspects of his study should be noted: (1) Specific points equidistant along the tunnel were graphically highlighted, thereby providing "looming" cues of depth change proportional to forward velocity, as the plane passes through the tunnel. (2) Grunwald experimentally manipulated the presence or absence of a 3D object representation of the predictor symbol. While this symbol was located at a position in perspective depth, it could take on the form either of a flat 2D cross or a schematic perspective aircraft. The latter provided additional information regarding the heading and pitch of the predictor, conveyed by its orientation in depth. This information could not be obtained from the flat cross. Grunwald found that little advantage was gained by this added 3D feature. There was some evidence that its presence allowed reduced control activity, but it did not improve flight path tracking accuracy.
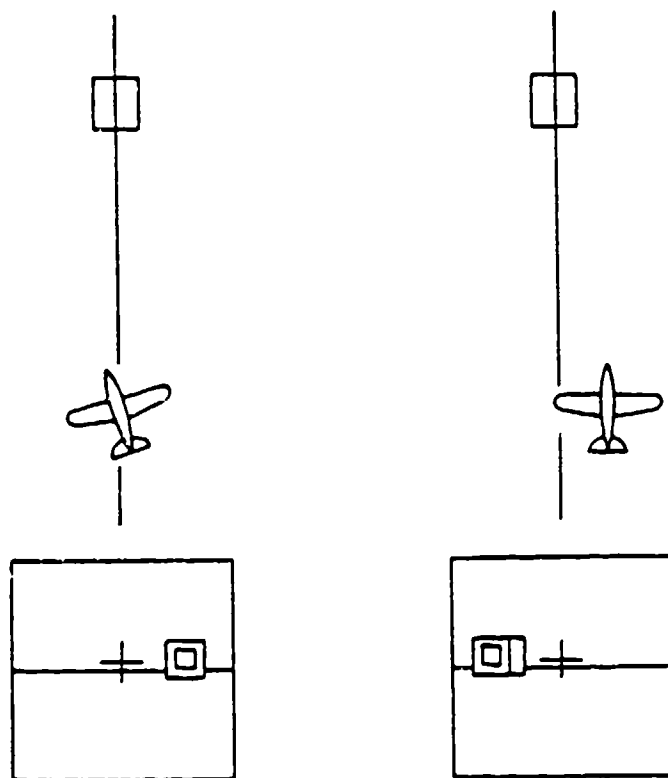
Adams (1982) describes a 3D perspective display proposed for commercial aircraft which incorporates a "follow-me" box (Figure 5.2). This is a 3D perspective representation of a box, sliding along the desired flight path, a fixed distance in front of the aircraft. Because it is drawn in 3D perspective, the displayed shape of the box will change as the pilot moves off the command flight path and gains a viewing perspective that is not from directly behind. Only in the latter position will the box's 3D edges be hidden, and will it be perceived as a 2D rectangle. Simulation flight tests of the display conducted with nine pilots revealed favorable acceptance.

TYPICAL FLIGHT
SITUATION

(x_{iB}, Y_{iB}, z_{iE})

X_i

Y_i

Z_i

X

Y

Z

(x_{iA}, Y_{iA}, z_{iA})

Sketch A

DISPLAY FOR
TYPICAL FLIGHT
SITUATION

Horizon

Reference
symbol

Sketch B

Sketch C

Figure 5.2. "Follow-me box" developed by Adams (1982).

However, pilot comments emphasized the need for precise information regarding the absolute value of deviations, which was not available from this more "holistic" display.

Wickens, Haskell, and Harte (1989a,b) tested a 3D perspective display with prediction and preview for MLS landing approaches using 20 pilots. Three conclusions from their experiment, bearing on the implementation of 3D cues, are relevant to the current discussion: (1) Airspeed was conveyed by the perspective size of the predictor, as this predictor was made to recede (contract for high airspeed) or approach (expand for low airspeed) in depth. This feature was more effective for airspeed control than was a separate linear indicator. (2) Connection of the corners of the preview flight path box by lines, as shown in Figure 5.1, provided a cue of linear perspective which facilitated judgments of orientation from the flight path. (3) Incorporating the cue of interposition by using hidden line algorithms on the flight path tunnel was particularly useful in resolving perceptual ambiguities of depth when the tunnel was viewed from below.

Nataupsky and Crittendon (1988) evaluated a perspective display for MLS landing with and without stereopsis (see 5.1.4), using Air Force pilots as subjects. Two pictorial representations of the flight path were contrasted: a simple "monorail," connected by posts to the ground, was contrasted with a series of 20 square boxes connected to the ground (like sign posts), with a constant "true size," which therefore diminished in display size with depth. The "sign posts" provided relative size as a depth cue, along with more precise information about error tolerance bands. The sign post representation supported better performance in the particular task studied by the investigators--the discrete response to sudden displacements from the flight path.

A major research program at the Naval Air Development Center has focused on the development and flight testing of another 3D perspective display concept developed by Filarsky and Hoover (1983) and Scott (1989). The display concept has been successfully flight tested in the air on a USAF/Convair NC-131, an F-14 fighter and in a low-fidelity helicopter simulator (Scott, 1989).

The studies carried out by Grunwald (1984) and Wickens et al. (1989a,b) have also examined the issue of frame-of-reference within the context of perspective displays. At issue is the extent to which the aircraft representation, rather than the horizon and tunnel, should move relative to the frame of the display. The comparative evaluations of the two reference frames by Wickens et al. supported a traditional inside-out frame, while the study carried out by Grunwald provided ambivalent evidence.

5.1.4 <u>Stereo enhancement</u>. Recent developments in 3D flight path displays have focused on the incorporation of stereoscopic cues. While a considerable amount has been written which discusses the potential advantages of this technology (e.g., Boff & Calhoun, 1983; Bridges & Reising, 1987) there have been only a small number of studies that provide solid empirical data regarding the efficacy of such displays in the dynamic flight environment. All have employed LCD alternating frame technology to present the stereo images.

A basic laboratory investigation by Kim et al. (1987) provided an empirical framework for considering the more applied studies in this area. Their study evaluated subjects' (nonpilots) tracking performance in a three-dimensional volume. Subjects manipulated a joystick to control a cursor cube. The objective was to track a target cube, which moved through the volume and was attached by a "post" to the ground. The investigators found that stereo viewing improved tracking performance when the display was poor in visual

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detail, but the advantage of stereo was no greater than the advantage offered by a textured ground surface. Furthermore, the two cues were not additive, in that providing stereo to the rich textured display yielded no further improvement.

Nataupsky and Crittendon (1988) examined the effect of stereo viewing in the MLS flight path display described in section 5.1.3. As noted in that section, two formats of depth information were employed to present the command flight path, with the "monorail" being less effective than the "sign post" display, in the task employed by the investigators (responding to sudden displacements from the flight path). Introduction of stereoscopic viewing improved response time with the less effective monorail display, but had no influence on performance with the more effective sign post display, a conclusion that mirrors the one drawn by Kim et al. (1987).

Reising et al. (1989) measured continuous flight path performance while subjects flew a tunnel in the sky with prediction and preview (see also 5.1.3). Subjects flew through both an easy and a difficult course (defined by the number and magnitude of course changes), and care was taken to incorporate realistic and effective nonstereo depth cues of relative motion, interposition, relative size, linear perspective, and ground texture. The investigators found that the addition of stereo viewing provided minimal advantage over the nonstereo version, although there tended to be a small stereo enhancement with the more difficult flight path.

Way, Hobbs, Qualy-White and Gilmour (1989; Way, 1989) implemented a full mission simulation on a fighter simulator, in which pilots flew both air-to-air and air-to-ground combat scenarios. Various features of the display world could be presented either in 2D perspective (Martin & Way, 1987) or 3D stereoscopic representation. Critical among these were a perspective

situation format, presented in both a ground and air mode, a HUD display of a flight path "highway in the sky," and a top-down map, or horizontal situation format. Stereopsis was implemented by time multiplexing images viewed through stereo glasses. Multiple performance measures were collected during both mission types, both with and without stereo viewing features. Consistent with the results of other stereo cockpit studies, Way et al. failed to find any advantage for stereo viewing of the flight path and tactical situation viewing in the full mission simulation. Pilots commented negatively on the loss of display resolution induced by the stereo images. In contrast, the perspective viewing created in the air-to-ground situation display was quite well received by the pilots. Some of the successful features of stereo implementation for static aspects of this simulation will be described below (Way, 1988).

Collectively, the results of these four empirical studies lead to the general conclusions that in a dynamic environment, stereoscopic viewing can sometimes be beneficial, but primarily for its compensation for the absence of other pictorial and motion cues, rather than for any enhancement of the effectiveness of well implemented cues that are already present. This finding is consistent with the conclusions drawn in section 3, which indicate that departures from the additive model are more likely to be observed under dynamic than static conditions. Indeed, one characteristic of the first three studies discussed above that probably enhanced the effectiveness of nonstereo cues is the dynamic property of the flight display which could provide relative motion cues. In fact, in the absence of motion cues, three additional studies described below have provided good evidence for the effectiveness of stereo in an aviation environment, although none of these involved flight path guidance.

Zenyuh et al. (1988) examined the effectiveness of stereo and of relative size cues in a tactical situation awareness display. Subjects were presented with a large number of displayed aircraft and were asked to count the number of a class of aircraft within a particular region of the 3D display. Their results indicated that both relative size cues and stereoscopy improved the accuracy of performance, and that those effects were relatively additive and of equal weight, supporting the conclusions drawn in Section 3. It should be noted that the total representation of depth in their display was fairly impoverished, in contrast to the typical research on flight path displays. That is, only relative size and stereo cues were available.

In a paradigm that was similar to that used by Zenyuh et al. (1988), Yeh and Silverstein (in preparation) presented subjects with a schematic perspective terrain, above which were presented two static objects. Subjects were to judge which object was closer to them, and which was of higher altitude, using either perspective only, or perspective with stereo. Various viewing aspects and stimulus configurations were used. The investigators found that stereo provided a clear enhancement. Furthermore, the pattern of results was such that the greatest stereo enhancements were obtained in those conditions (and for those judgments) for which perspective viewing was poorest. These results are consistent with those observed by Kim et al. (1987).

A second aviation-relevant study by Way (1988) examined a pilot's ability to discriminate the octants of a wire frame "sphere," surrounding an aircraft. This sphere was meant to simulate the functional status of on-board sensors. Here also, as with the Zenyuh et al. study, nonstereo depth cues for the "front" and "back" sides of the sphere were impoverished, provided only by height in the visual field (i.e., the sphere was viewed as if from slightly

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above). Under these circumstances, stereo viewing led to a substantial

reduction in the number of confusions between the near and far surfaces of the

sphere.

Way (1988) also reports a study in which stereo was used to highlight

critical regions of an aircraft system diagram by making these "pop out" above

the image plane. He found that color coding was more effective than stereo

coding in reducing the time required to identify the highlighted item.

5.1.5 Ground texture. A major concern in the development of flight

path displays has been determining the appropriate 3D cues for ground

simulation to provide information for perception of forward velocity, altitude

and heading during approach or low level flight. There is no doubt that such

information, in the form of textural gradient and expansion is useful (Gibson,

1979; Langewiesche, 1944). Recent research has focused on determining which

particular elements of ground texture are most useful, given the tradeoffs in

computer display technology necessary to implement some of these various forms

of texture. These data have a direct relationship to the research of Cutting

and Millard (1984) discussed in Section 3.5, regarding the necessary depth

cues for slant perception, although that research is not generally cited.

In the simulation research on this issue, a general conclusion seems to

be that "more is better." For example, Reardon (1988) compared the ability of

the four textures shown in Figure 5.3, to support accurate judgments of

landing touchdown point, and found a monotonic improvement in performance as

more depth cues were added, from left to right in the figure. Wolpert (1988)

evaluated the two components of the grid texture shown in the third panel of

Figure 5.3: the parallel along-flight path lines, which provide an altitude

cue of linear perspective, and the perpendicular cross-flight path lines,

which provide a cue of spatial frequency or texture gradient. The particular
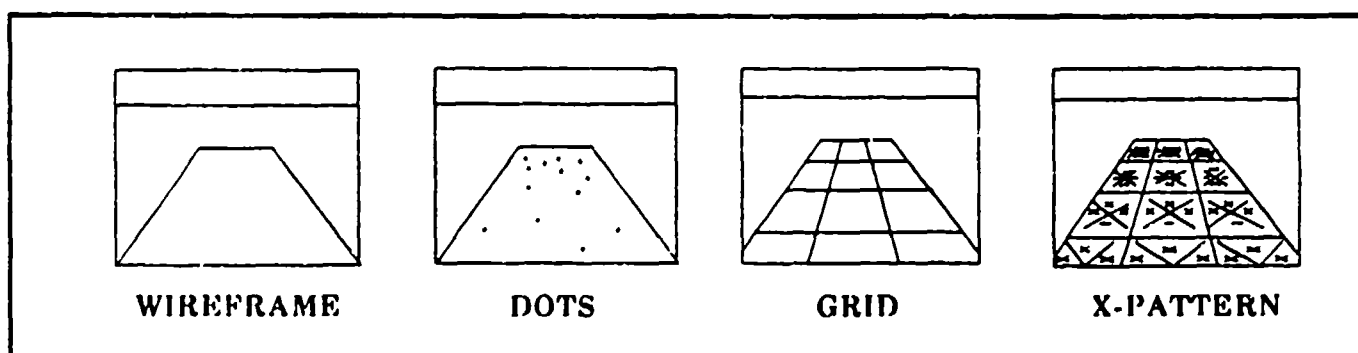
WIREFRAME DOTS GRID X-PATTERN

Figure 5.3. Four ground textures used in landing judgment study by Reardon (1988).

cues of altitude provided by these two orthogonal linesets are sometimes
referred to as splay along the flight path, and compression, across the flight
path. Subjects in Wolpert's simulation attempted to maintain altitude with
each of the two patterns, or with their combination in the grid. Data
indicated that parallel texture and its derivative cue of linear perspective
or splay cue were the most important components for the slant perception
necessary to achieve altitude control. The advantages of parallel texture
were the same, whether presented alone or when combined with perpendicular
texture so that a grid was formed. Compression seemed to offer little
advantage.

A somewhat different conclusion, regarding this usefulness of splay was
obtained by Johnson, Tsang, Bennett, & Phatek (1987) and O'Donnell, Johnson,
and Bennett (1988). Using a forward-looking simulation which was disturbed
along translational, but not rotational axes, these investigators obtained
results indicating that compression supported altitude control, but not splay.

It appears that the results supporting splay and those supporting
compression are not altogether in conflict. The usefulness of one versus the
other source of information for control depends upon the particular
constraints placed upon the vehicle (e.g., hover versus forward motion). In
Wolpert's study, when forward travel was required, altitude information
conveyed by compression was degraded by the flow of the perpendicular texture
across the visual field, whereas the appearance of splay was unaffected by
forward motion. Hence, it becomes a perceptually more reliable cue. In
stable hover, however, when forward motion is not involved (Johnson et al.,
1987), compression is only affected by altitude, and it becomes as effective
as splay, if not more so (Flach, personal communication).

A recent study by Weinstein (1990) compared a perspective splay display, with a more conventional forward-looking ADI for control of altitude and heading in a helicopter simulation. While perspective splay did not provide better performance, Weinstein's data suggest tnat control effort was reduced and more resources were freed to deal with a concurrent task, when using this display.

Kleiss, Hubbard, and Curry (1989) examined the effects of object detail and object density of computer-generated imagery in simulator altitude control. Their conclusion is that such control was better supported by a larger number of crudely drawn objects (i.e., polygons) than a smaller number of more "realistic" objects (e.g., trees). Hence, if computational image generation power is a limiting bottleneck, then such power would be be.t allocated to creating a dense but abstract or schematic set of ground objects.

Another important tradeoff in dynamic ground texture simulation is with display update or frame rates. An early study by Wempe and Palmer (1970) examined the influence of varying frame rates on landing approaches. While high update rates provide greater simulated realism, Wempe and Palmer concluded that increasing update rate above 0.5 Hz did not improve landing performance. However, it should be noted that their study incorporated only random dot ground texture, and did not include the more complex line textures shown to the right side of Figure 5.4.

In summary, the previous studies suggest that certain kinds of control tasks may best depend on certain kinds of cues (e.g., splay, compression). Analysis of the optical information necessary to control can provide guidance of the optimal cue for a particular control task. However, across different tasks, more information appears to be better, and any textural information, whether in the form of lines, grids, or spots, should be regular, not randor

5.1.6 Summary and conclusion. The current data strongly suggest that well implemented 3D technology, capitalizing on the variety of monocular and binocular cues available to human perception, can be used to enhance performance in aviation-related environments. Even so, however, the number of studies that have systematically paired 3D displays with corresponding 2D versions containing the identical information are few, the results of such studies are ambivalent, and more research of this sort certainly is needed. This is particularly true in light of the fact that there may be shortcomings of 3D displays inherent in their ambiguity when presenting distance and position information. Thus far, studies which have examined 3D applications for flight path control and guidance have failed to incorporate tasks that require precise check reading of flight parameters (which would be directly available from traditional displays), although subjects in Adams's (1982) experiment were explicit in noting the absence of such information from the perspective display.

With regard to the specific cues necessary to achieve a good 3D representation, the current data remain generally consistent with the "more is better" model drawn from Section 3. Stereoscopic cues appear to be neither more nor less effective in their influence on performance than other cues, particularly when the display is dynamic. The data seem to suggest some departure from the linearity of an additive model in the upper range of cue numbers. That is, when a number of depth cues (whether mono or stereo) are already present, performance is not improved by the addition of more cues, perhaps reflecting a ceiling effect. This departure from the additive model seems to be particularly true when motion is present. This conclusion does not diminish the potential importance of stereoscopy in flight deck displays. Its presence can certainly enhance depth perception with static displays, or

lessen the need for the computer-intensive imagery necessary to create other cues in a dynamic mode. Finally, the relatively small number of studies upon which the above conclusions are drawn does not begin to address the full problem space. Clearly, a great deal more research is needed in this area to explore the costs and benefits of stereo technology.
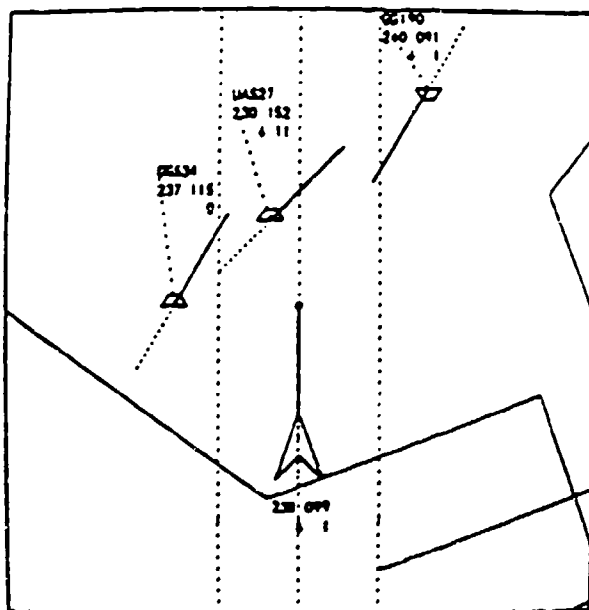
5.2 Air Traffic Control Displays

The air traffic control environment is a natural one for the introduction of 3D display technology, because of the need for controllers to solve problems involving all three dimensions of Euclidian space by recommending horizontal and vertical maneuvers. Hence, it is surprising that relatively little work has been done in this area. Most prominent is a program of research carried out at NASA Ames Research Center, which has focused on the Cockpit Display of Traffic Information or CDTI (McGreevy & Ellis, 1986; Ellis, McGreevy & Hitchcock, 1984, 1987; Smith, Ellis, & Lee, 1984). Using a systematic approach to optimizing perspective display design, Ellis and his colleagues developed the display shown in Figure 5.4(b), which presents an "outside-in" view of the pilot's own ship, along with the position of other nearby aircraft. Noteworthy here is the presence of a number of artificial aids or symbolic enhancements to compensate for the shortcomings of perspective displays in precise checkreading. These enhancements, discussed in Section 4.1, include the "post" upon which each aircraft stands, the second post, in front of each, which unambiguously specifies the course heading along the ground, and the "x" on each post, which corresponds to the altitude of the pilot's own aircraft. This feature allows precise determination of whether an aircraft is above or below the pilot's aircraft. Smith, Ellis, and Lee (1984) carried out a comparative evaluation of this display format, contrasted with the 2D plan view shown in Figure 5.5(a). In their simulation experiment, they

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(a)   (b)

PLAN-VIEW DISPLAY   PERSPECTIVE DISPLAY
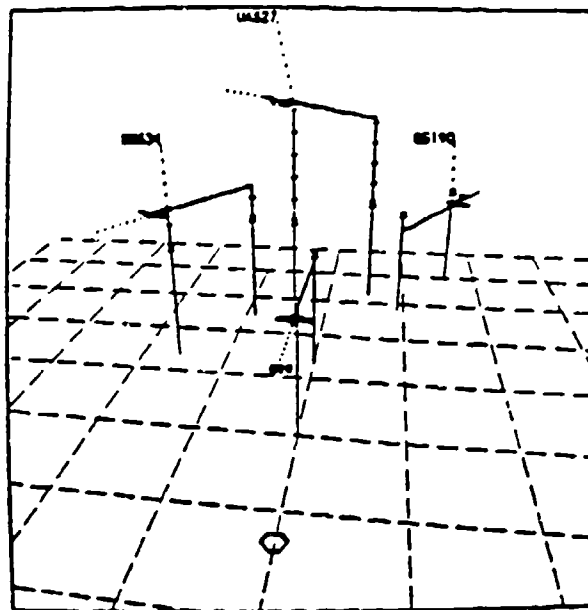

Figure 5.4. (a) Plan view display; (b) Perspective display for air traffic,
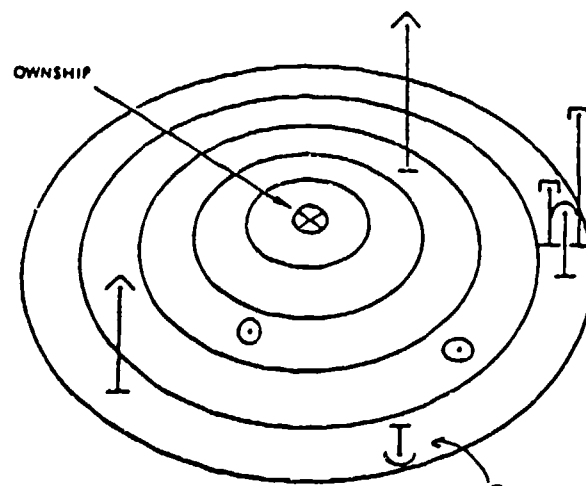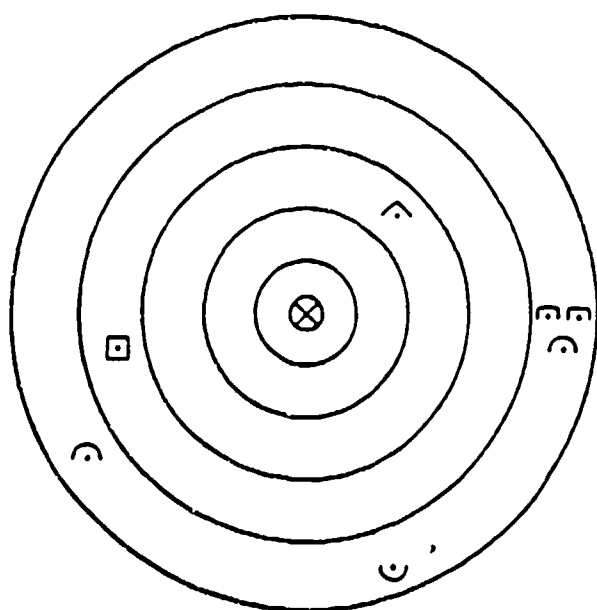developed by Ellis, McGreevy, and Hitchcock (1984).

Figure 5.5. Plan view display (left) and perspective display (right) for air intercept control, evaluated by Bemis, Leeds, and Winer (1988).

found that the 3D version was viewed more favorably by pilots. Ellis, McGreevy and Hitchcock (1984) found that the perspective display facilitated a greater use of vertical corrections in response to potential collisions.

A similar prototype was developed by Bemis, Leeds, and Winer (1988) to support the performance of Navy air intercept controllers, who must detect an airborne threat, and then select the closest friendly aircraft to send to intercept that threat. Figure 5.5(a) and (b) contrast the 2D and 3D versions of the two displays that were compared. Their data revealed a substantial advantage for the perspective display, particularly in reducing the errors made in picking the closest intercept.

In light of the success of both of these research programs, it is surprising that more work has not been carried out in this area, either examining conventional ATC displays or examining the feasibility of employing stereoscopic displays for this purpose. The experiment by Zenyuh et al. (1988) described in Section 5.1.4 was not targeted directly at air traffic control, but did suggest the usefulness of stereoscopic displays in identifying the relative position of objects in a 3D volume. Williams and Garcia (1989a,b) have proposed that their mirror-driven volume-visualization display could serve as an ideal medium for ATC displays, as the controller could literally look over and walk around a dynamic volume of the airspace (see Section 4.1). However, this concept remains a long way away from implementation.

5.3 Meteorology

Meteorological research and observation generate large quantities of multidimensional data. For each (xyz) spatial coordinate in the atmosphere, a minimum of five principal atmospheric variables are generally of interest over time: temperature, pressure, moisture, wind direction, and speed (Grotjahn,

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1982). Frequently, the interactions among these quantities or additional variables must also be considered. It is not surprising then that satellite, radar sensor systems, and sophisticated computer technology capable of generating simulations of complex atmospheric phenomenon, have produced voluminous and complex geographical data sets. Researchers in the atmospheric sciences and those involved in operational weather forecasting need to assimilate these data in a timely manner. Traditional two-dimensional planar displays are inadequate for this purpose. The need to preview, analyze, and present such large amounts of information has prompted the use of 3D static and animated displays. Figure 5.6 provides prototypical examples of two such displays.

The depth dimension is typically expressed in any one or combination of the following formats:

(1) Colors are arbitrarily assigned to different levels of data (false color), or gray scale images are used,

(2) Novel vector plots are used in which arrow length, deflection and arrowhead size each reflect different data levels,

(3) Contours are employed to display variation in scalar values,

(4) Sequences of two-dimensional contour (or sometimes perspective) graphs are stacked along the plane perpendicular to the plane of the graphs,

(5) Perspective views of a 3D object or of the trajectories (paths) of the data points in 3D space are used,

6) True or artificial stereography is used. True stereography uses satellite data which is actually recorded in stereo. Artificial stereo constructs pairs of stereoscopic pictures in part from
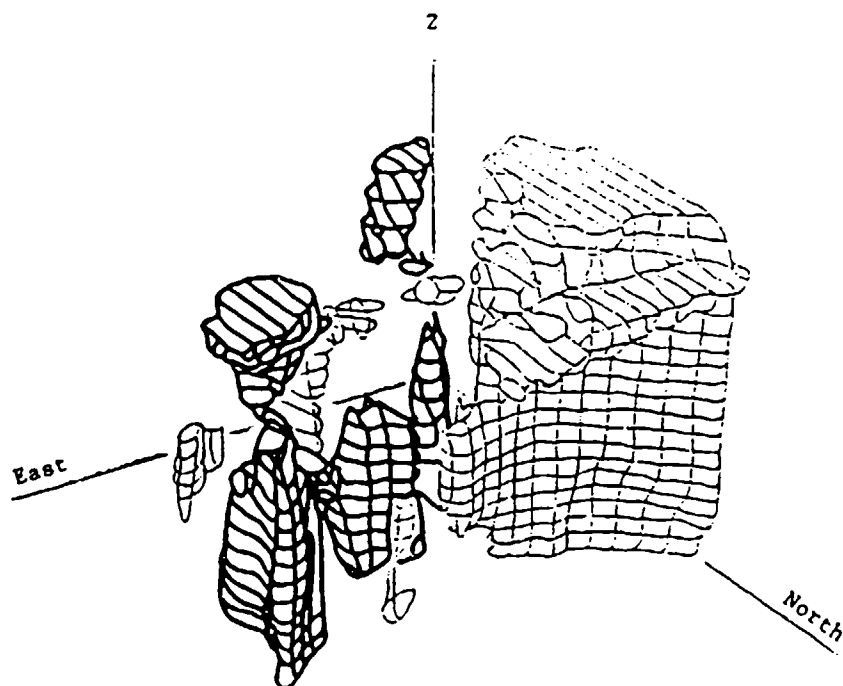
Perspective view of up- and downdrafts, 1308 PST 2 March 1978. Contour surface encloses the region of updrafts >4 m/s. Light contour surface encloses the region of downdrafts >4 m/s. Vertical scale has been exaggerated by a factor of 4. From Moninger (1980a).
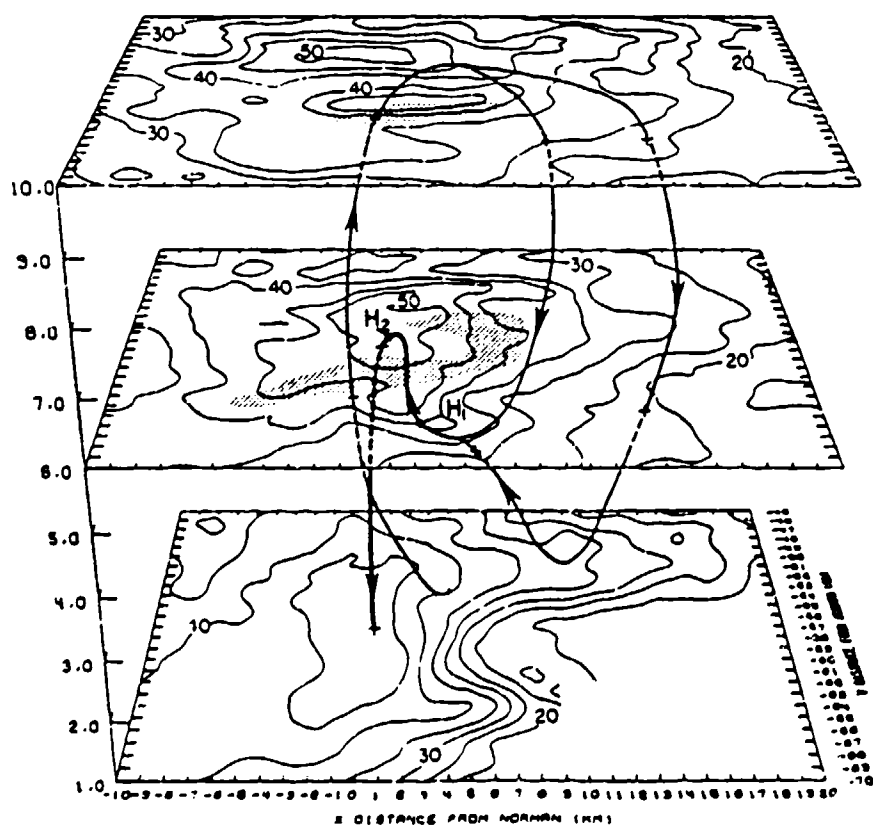
Three-dimensional perspective display of storm reflectivity (light lines, dB(Z)), updraft (shaded areas ≥20 m/s interior unshaded ≥40 m/s), hypothetical embryo trajectories (before H₁), and computed hailstone trajectory (after H₁). H₁H₂ denotes region of maximum hail growth (after Nelson, 1980).

Figure 5.6: Two examples of perspective meteorological displays. From Moninger & Nelson, 1980.

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computer-generated images. The third dimension (height) represents any scalar quantity.

Applications using the latter two formats (which employ display representations of depth) will be discussed below. Note that evaluations of these display techniques in the meteorological field have been purely informal and subjective.

5.3.1 <u>Perspective</u>. Hasler, Pierce, Morris and Dodge (1985) applied a perspective technique to display several kinds of meteorological image data. The procedure combined information from a visible and infrared image pair, obtained by satellite (an artificial illumination image may be substituted for the visible image), and combined the input into a single perspective image. The infrared image provided information necessary to construct the 3D surface of the final image (a cloud) while the visible image supplied the coloration or shading information necessary for texturing. This shaded perspective display was found to be superior to a wire-frame perspective display, on the basis of subjective judgments of realism.

By systematically selecting and combining a series of "eye-points," defining the viewing azimuth and elevation angle, and "viewpoints" (location of the point being viewed) and constructing the image as it would be seen looking from the eye point towards the view point, a movie was produced which employed motion parallax as an additional depth cue. An impression of "flying over" or "moving through" the display was reported by viewers. Additional depth cues were given by using shadows and perspective when incorporating annotation representing latitude and longitude into the image. The annotation appeared to float over the clouds.

Kelley, Russo, Eyton, and Carlson (1988) also developed a perspective technique, Model Output Enhancement (MOE), which generates mesoscale weather

forecasts. The resulting display uses both color-class planar maps and color-class maps overlaid on perspective plots of terrain. It was felt that the use of 3D perspective provided the viewer with greater "spatial feeling" of the mesoscale temperature field and aided in the interpretation of the data.

At least two problems have been noted when perspective alone is used as a depth cue (Grotjahn & Chervin, 1984). There can be a "line of sight" problem, that is, ambiguity as to where in a 2D viewing plane a data point actually lies. This problem can be attenuated by (1) using a shadow cast (projection) on the sides of a volume box enclosing the data points (although this adds to display clutter), (2) varying the size of the symbol representing the data point depending on its "distance" from the viewer, (3) employing stereoscopy, or (4) allowing rotation of the object, thus enhancing the viewer's ability to construct a 3D mental image (Grotjahn, 1982).

Grotjahn also observed that viewer disorientation is possible when viewing a perspective object from different angles unless the different angles are shown simultaneously (which again increases display clutter).

5.3.2 Stereo enhancement. Hasler, Desjardins, and Negri (1981) describe a general technique for displaying multidimensional data sets using artificial stereo. As discussed in Section 4.2, one way of generating an artificial stereogram consists of an original image and a second computer-generated image produced by shifting the pixels in the original image to the right. The computer-generated image is colored blue-green and superimposed over the original image which is colored red. The user views the image display with red/green anaglyphic glasses which direct each image of the pair to the right and left eyes, respectively, creating a stereo image. Hasler et al. report that stereo presentation allows the viewer to more easily and

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intuitively assimilate the information contained in the image (although this was not empirically evaluated).

Papathomas et al. (1987) demonstrated that anaglyphic stereo animation can portray large four-dimensional (space and time) data sets. They transformed the numerical data output of a simulation program which models time evolution of weather episodes into stereo animation sequences of storm clouds. In rendering the graphics of the clouds, Papathomas et al. found that a "particle system" format, in which all points in the volume of a cloud are illuminated, was superior to a wireframe or surface rendering of the object (a cloud). The particle system is suited to the depiction of fuzzy objects. Superiority in large part was judged on the basis of subjective scene realism. Papathomas et al. also found that graphic realism could be further enhanced by randomly "jittering" the local random-dot distribution relative to the background, that is, movement of cloud particles aided in depth perception.

Hasler (1981) describes the techniques and applications of stereographic images derived from actual stereo observations (from Geosynchronous Satellites). Unlike artificial stereo techniques, a major advantage of true stereographic images is that they can be used to make high-precision cloud height measurements. Determination of height involves parallax measurement of the image. The location of a feature on each of the images of a stereo pair is measured by using one of three techniques, all of which involve shifting one image until parallax for a feature is eliminated. Height calculations can be derived from the amount of this parallax shift.

While true stereography is more useful quantitatively, artificial stereo viewing provides a higher visual quality and greater stereoscopic view.

In summary, it appears that the development and evaluation of 3D meteorological displays is in a far earlier stage than the corresponding

development for flight displays, despite the potential benefits that this technology has to offer.

5.4 Teleoperator and Robotics

Teleoperation involves the remote control of machines. Typically, a human operator contributes his/her perceptual-motor and cognitive skills to a manipulation task via a machine interface located at some distance from a hazardous or inaccessible environment. Visual or graphic displays are necessary to provide the human operator with unambiguous information about the work environment. Much of this information is three-dimensional, and it goes without saying that some form of 3D representation is valuable. The identification of the specific display cues affecting spatial perception, then, is essential to facilitate performance. Many of the studies conducted in the context of teleoperation have focused on the relative utility of monoscopic and stereoscopic displays and on visual enhancements. These are described below.

5.4.1 Monoscopic v. stereoscopic displays. An early study by Pepper and Cole (1978) suggested that stereoscopic viewing systems did not significantly contribute to successful remote undersea manipulation. This was surprising given the many direct-viewing studies where the superiority of binocular performance over monocularity had been demonstrated. Pepper et al. (1981) explored the possibility that manipulation performance under mono and stereo viewing is a function of the interplay of a number of factors: environmental visibility conditions, task type, and operator experience. Three experiments were conducted to assess relative performance of binocular disparity cues over monocular cues across different task types, experience levels and visibility conditions.

A laboratory peg-task was used in the first experiment. This task was comparable to such real world tasks as drilling, tapping, threading, and connecting, and primarily involved alignment in the x and y (horizontal and vertical, respectively) planes and rotational movement. In the peg-task, monocular cues were critical for object recognition and spatial location while stereo cues were considered less relevant. Highly practiced subjects were used. Performance times were examined under three levels of visibility (clear, moderate, and stereo). Even though experimental design was biased against the stereo and severe visibility conditions, performance time was found to be facilitated by the stereo display.

In the second experiment the peg-task and three levels of visibility were used again; however, this time subjects were used who had some experience with teleoperation but were unfamiliar (unpracticed) with the specific task at hand. Nonvisual factors were minimized while monocular depth cues were maximized. The mono-stereo differences were not found to be significant statistically, although this was not surprising since the experimental design emphasized the use of monocular depth cues.

A messenger-line feeding task (comparable to such tasks as line attachment, sample gathering, and simple salvage tasks) was employed in the third experiment. This type of task requires alignment in the x, y, and z planes in a visual scene containing many conflicting depth cues. Under all levels of visibility, stereo performance was found to be far superior in this type of remote manipulation task due to the reduced level of available monocular cues. Further, stereo TV was found to be degraded less by poor visibility than was mono TV.

This series of experiments demonstrated that the level of improvement due to stereo TV is dependent upon the complex interaction of visibility,

task, and learning factors. It was shown that stereo TV displays are superior to mono under most of the conditions tested. As scene complexity and object ambiguity increased, the advantage of the stereo display became more pronounced.

Kim, Takeda, and Stark (1988) quantitatively assessed the utility of superimposing visual enhancements onto a flat video screen to assist operators in performing telemanipulation tasks. A teleoperator simulator with a two-degrees-of-freedom joystick and five-degrees-of-freedom manipulator was used. In the first of two experiments, subjects performed pick-and-place tasks under three visual conditions: direct view, monoscopic TV view, and monoscopic TV view with visual enhancements. The objects to be picked up and the boxes in which they were placed were restricted to the plane of the robot base. Visual enhancements included a vertical reference line (indicating the vertical height of a point from the base plane; see also Section 4.1), a reference grid, and a stick figure model of the manipulator gripper and its projection. In the second experiment, pick-and-place tasks were performed under five visual conditions: direct view, two adjacent views, visually enhanced TV view, two perpendicular TV views, and a stereoscopic TV view (a helmet-mounted display was used). Objects to be picked up were arbitrarily positioned. Practiced subjects were used in both experiments. Time to task completion and task success rate were used as performance measures.

Direct view provided best performance overall. Superimposing the enhancements was found to greatly assist human performance of telemanipulation tasks, relative to the mono TV display alone, when the objects were all located on the robot base plane. Visual enhancements also benefited performance relative to the mono TV when the objects were randomly positioned; however, the accrued advantage was not as pronounced or reliable. It was

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suggested that this was because the visual enhancements did not "explicitly indicate object orientation." The results further showed that when subjects were provided with only the monoscopic view, occlusion was the potent cue used to determine location of the manipulator gripper relative to the target object.

The overall conclusion in this set of experiments was that on-the-screen visual enhancements greatly facilitate task performance when objects are positioned along the robot plane. When objects are randomly positioned, additional research is needed to determine how more reliable performance may be achieved.

Kim et al. (1987) evaluated monoscopic and stereoscopic graphic displays wit! and without grid or reference lines by employing a three-axis manual tracking task. Three perspective display parameters were varied: elevation angle, azimuth angle, and object distance. Root-mean-square (RMS) tracking error was used as the quantitative performance measure.

It was shown that the grid did not improve tracking performance. The reference line served as an important depth cue and greatly facilitated performance for mono-perspective displays. The stereoscopic display permitted lowest RMS tracking error over all visual conditions, even when the grid or reference lines were not present. Further, at extreme viewing elevation angles, the stereoscopic display provided good performance, suggesting that it was robust against elevation angle.

Similar results were obtained in the study carried out by Kim, Tendick, and Stark (1987) discussed in Section 3.1. Stereoscopic viewing benefited a 3D tracking task unless the task was augmented with symbolic enhancements (a post) and a perspective grid.

5.4.2 Stereo viewing implementation. A discussion of issues related to positioning of stereo cameras for teleoperation was presented in Section

4.2.3. A general conclusion, which will be reiterated here, is that hyperstereo displays, in which the convergence angle between two imaging cameras is greater than the angle formed by the two eyeballs, provides an advantage for many teleoperator manipulating tasks (Diner & von Sydow, 1988).

5.4.3 Summary and conclusions. For some simple teleoperation tasks, monocular depth cues, used in conjunction with the operator's cognitive depth cues (e.g., derived from experience) may be sufficient for successful performance. However, with increased task complexity, these cues may be unavailable. In some situations, providing visual enhancements, such as reference lines, and adequate perspective parameters, may be adequate to compensate for the inadequacies of a monoscopic display. Stereoscopic displays, however, provide binocular depth cues which significantly enhance performance, particularly when visual enhancement cues are not presented.

5.5 Other 3-Dimensional Graphics

A number of other potential applications of 3D displays have not been described above. These roughly fall into two categories: static graphs that allow operators or scientists to inspect data, and dynamic or interactive graphics that allow users to manipulate and explore visual information represented in three dimensions. While many examples of 3D graphics of both kinds exist, very few have been subjected to empirical evaluation and experimental manipulation.

5.5.1 Static graphs. In spite of the increasing popularity of 3D graphs to represent data with three or more variables, of the sort shown in Figure 5.7, there seems to be almost a total absence of empirical data bearing on its effectiveness. For example Tufte's (1983) classic treatise on the graphic display of data contains only one example of such a graph (the one shown in Figure 5.7), out of over 200 figures. This absence is unfortunate
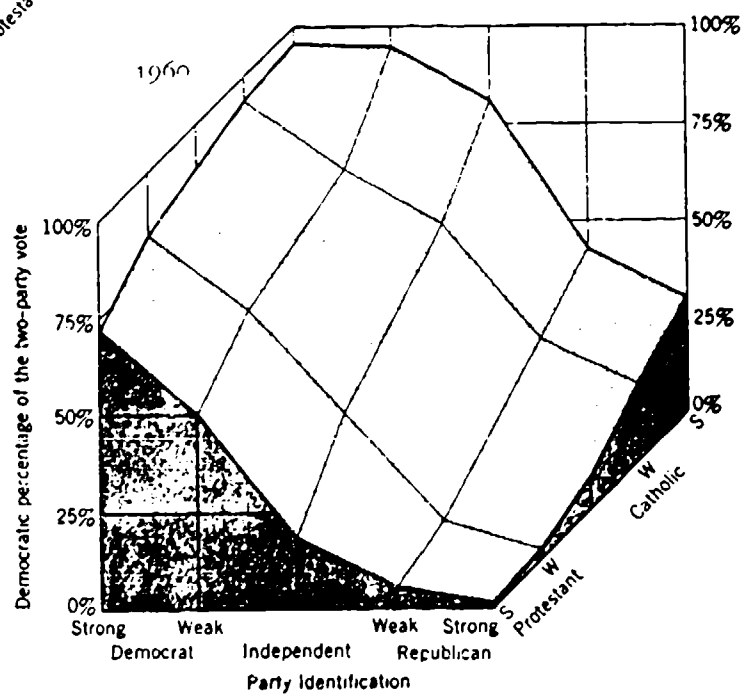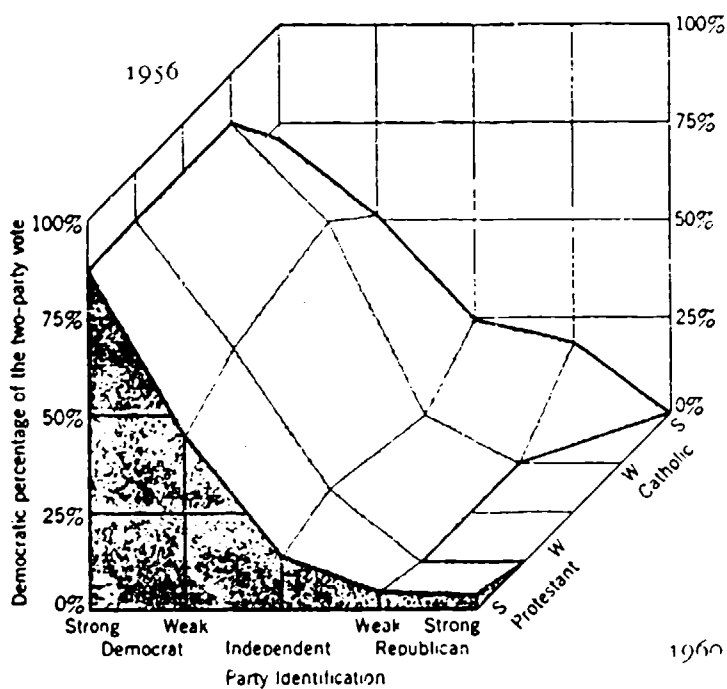
Figure 5.7. Example of 3 dimensional graphic display. Philip E. Converse, "Religion and Politics: The 1960 Election," in Angus Campbell, Philip E. Converse, Warren E. Miller, and Donald E. Stokes, Elections and the Political Order (New York, 1966), 102-103. Reprinted from E.R. Tufte (1983). The Visual Display of Quantitative Information. Cheshire, CT: Graphics Press.

because graphs of this sort have applicability not only for data representation, but also potentially in airborne applications, to represent operating "envelopes" or performance parameter limits that depend upon three or more variables (e.g., airspeed, altitude, and turn radius). One exception is an experiment by Jensen and Anderson (1987), who compared correlational scatter plots rendered by dots (Figure 5.8(b)) or by 3D "mountains," whose height at any one point is proportional to the density of the points (Figure 5.8(a)). Subjects' judgments of the degree of relationship between the x and y variable were actually more accurate with the scatter plots than with the 3D rendering. A second piece of empirical data is provided by an experiment by Liu (1989) who compared scientists' ability to understand the clustering of data, in a table of associations, when strength of association was either coded by color, or by the height of a third dimension above the N x N matrix. Liu found that 3D coding produced slightly faster but considerably less accurate performance. Collectively, neither of the two studies provides consistent evidence for an advantage of 3D renderings of data relations.

The absence of more empirical research in this area forces us only to outline a number of salient issues that should be considered as such graphs are constructed. Among these are:

(1) For graphs that depict functional relations of the form $y = f(x,z)$ (or experimental data in which y is a dependent variable affected by x and z), how are such data assigned to axes to allow best interpretation? Conventional rendering typically assigns x and z to a horizontal surface and y to a vertical one, as shown in Figure 5.7. What assignment should be made if x is a single independent variable, and y,z are bivariate dependent variables?
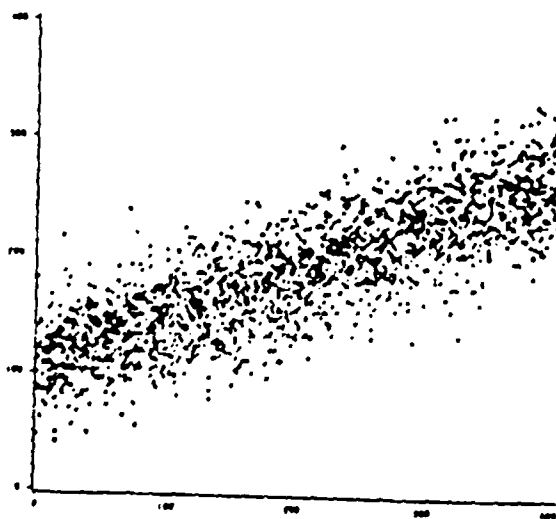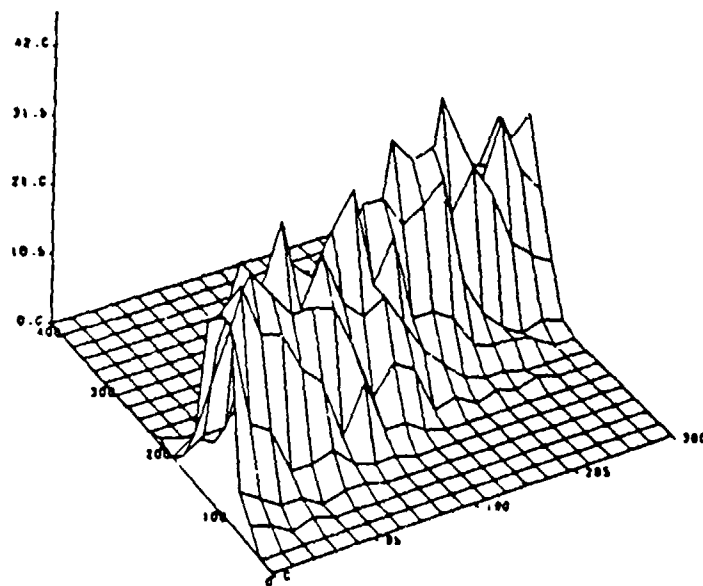
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Figure 5.8: (a) 3D rendering. (b) 2D rendering of correlational data by Jensen et al.

(2) Using 3D graphics, should protrusions representing the separate data points be connected to form a surface as in (Figs. 5.7 and 5.8(a)) or remain separate? While experimental data are not available on the point, it is apparent that the lines created by those connections do add important visual features that reflect the surface shape, and so are probably advisable.

(3) Considering the same issues addressed by McGreevy, Ratzlaff, & Ellis (1986) in Section 4.1, what should be the optimum azimuth and elevation viewing angle which will minimize perceptual distortions?

(4) As we noted in Section 1, 3D displays can incur biases and ambiguity regarding the precise estimation of distance at different depth planes. It is clear, for example, using a parallel projection, such as that shown in Figure 5.7 that bars of equal physical height (i.e., measured in screen pixels) will not yield equal perceived height. Rather, size-distance invariance computation will exaggerate the perceived height of the more distant bar. At the same time, use of perspective geometry which would compensate for perceived distance would not take into account the "cues for flatness" that would lead the observer to perceive less depth than is really the case. The point here is that the amount of visual distortion created (and therefore compensation needed) by size-distance invariance is not well established. Where absolute height measurements on the ordinate are required, these should be augmented by tick marks on the bars.

(5) There is reason to believe that 3D representations of data are not of value unless they convey a pictorial relation between variables that cannot easily be discerned by two 2D "slices." Typically any

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additive effects or linear interactions can easily be understood by two - 2D graphs. Where interactions involve higher-order terms (see for example Figure 5.7), the value of the 3D representation grows accordingly.

5.5.2 Dynamic interactive graphics. Two general categories of applications are found in dynamic computer-generated displays. The first of these actually involves a set of applications to real-time computer-based graphics for such applications as computer-aided design (CAD), computer-aided manu:acturing (CAM), and interacting with data bases. For example, Barfield Sandford, and Foley (1988) have considered the advantage of different surface representations in facilitating the 3D mental rotation of CAD images. They found that shaded surfaces allowed faster manipulation than did wire-frame surfaces. Chen, Mountford, and Sellen (1988) have explored different cursor positioning devices for manipulating 3D images, and found that there is a compatibility between the natural rotation of the image in three dimensions, and a spherical cursor that has a similar 3D rotational capability (relative to 2D and 1D manipulanda). Huggins and Getty (1984) examined issues related to control-display compatibility when using the multiplanar "space graph" display described in Section 4.3.2. While numerous other examples of 3D control-display ensembles for CAD/CAM-like operations exist, these are typically void of valid human performance data.

Beaton, DeHoff, Weiman, and Hildebrandt (1987) also evaluated cursor-position devices for a 3D display workstation. Operator performance on a cursor positioning task was compared using three types of input devices and two modes fo displaying depth information, a linear perspective display and a time-multiplexed stereoscopic display. The three input devices used were a

trackball, a mouse, and a 3D thumbwheel. The trackball provided unrestricted cursor movement along the three axes of the workspace (free-space movement). The mouse allowed for movements in either the xy, xz, or yz display planes (plane-oriented movement) while the thumbwheel provided for vector-oriented movements, or movement through separate cursor control for each axis. The vector-oriented device was found to provide the greatest positioning accuracy. Rapid cursor movements in the y z plane (depth) were found to be more difficult than were movements in the more conventional xy plane.

Beaton & Weiman (1988) extended the above study evaluating cursor-positioning to include two additional vector-oriented movement devices: a set of planar thumbwheels and a slider device. Again it was found that the vector-oriented input devices provide more accurate and faster 3D cursor positioning than either plane-oriented or free-space input devices. These results were attributed to the observation that inadvertent motions of highly coupled input devices (i.e., free-space and plane-oriented) produce undesirable movements of the cursor. Unlike the situation with a 2D display system, all motions of such input devices correspond to displacement in a 3D workspace.

In addition, lower cursor positioning errors were consistently associated with the stereoscopic display mode for all input devices except the planar thumbwheel (in which errors across display mode were equally low). However, it was noted that cursor-positioning time was similar across display mode, suggesting that users were not aware of their cursor-positioning errors.

Scientific visualization, the second area of dynamic interactive graphics, is an emerging field that also capitalizes on dynamic computer-generated 3D representation (Alexander & Winarsky, 1989). Here the interest is in creating a 3D rendering of a phenomenon of interest to the scientists,

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which they may interactively "explore." Such phenomena may involve the dynamics of storm systems, the behavior of the upper atmosphere in reflecting or absorbing radiation, the structure of complex molecules, the fracturing of metals under stress, or abstract mathematical relations. Figure 5.9 presents the static rendering of a severe thunderstorm which has assisted one scientific team in understanding the airflow with such a system (Wilhelmson et al., 1989).

Generally such renderings in scientific visualization are based upon intuitions on the part of the graphic artist working with the scientist, and are not yet based upon a set of empirically based principles. In an interesting convergence of technologies, however, the objective of visualization is to create a virtual world of the phenomenon of interest which the scientists can explore and through which they may navigate. The objective of the aviation display designer is, increasingly, to capture the spatial world through which the pilot must navigate in a virtual display like that shown in Figure 5.1. Thus, the objectives of these two technologies are actually quite close, and it is likely that design lessons learned in each can be exploited in the development of the others.

Figure 5.9. Static rendering of dynamic visualization program portraying the evolution of a severe thunderstorm (from Wilhelmson et al., 1989). Courtesy of National Center for Supercomputing Applications.

6.0 CONCLUSIONS

There is little doubt that 3D renderings, if carefully constructed, can provide a "natural" viewing of a variety of environments, which is aesthetically pleasing. Furthermore, the literature reviewed in the preceding pages provides many examples of domains in which such renderings have been shown to be useful when compared with well constructed 2D renderings. Examples of this usefulness will proliferate as computer graphics technology continues to improve in speed and resolution, and as the fledgling industry of stereo viewing devices begins to grow. Stereoscopic viewing, which is sometimes considered to be "true" 3D, often provides an advantage over non-stereo, although the advantage is not necessarily more pronounced than that offered by other salient cues related to motion parallax and occlusion. The review has also highlighted certain areas where neither 3D in general nor stereo in particular has proven advantageous, particularly in dynamic flight deck displays. An encouraging aspect of the research reviewed is the extent to which general findings from basic research, related to cue dominance and the interaction of static and dynamic cues, are substantiated in more applied contexts.

One conclusion drawn from the review is the obvious one that more empirical data are needed on the interaction between multiple cues, and between other variables, in complex environments. Research in applied contexts needs to be more clearly established, for example, the difference between depth cues used for judging object identification, object location, and surface slant. It needs to establish more clearly how the utility of different cues is modulated by the transition from static to dynamic displays, as frame rate is increased. And a better understanding of the difference between holistic judgments of general location and analytic judgments of

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specific distance must be sought. How can technology combine to optimize both of these? These questions require more empirical data before designers can make informed choices about the simplicity (or complexity) of technology necessary to create 3D renderings for a given application purpose.

Finally, we close with a plea, which is appropriate for the choice of any new display technology. Introduction of that technology for a specific purpose should be preceded by a careful analysis of the users' information needs, and the general characteristics of that information. Is check reading needed? Will distortions lead to serious errors? Is the information dynamic? Careful consideration of these questions should ensure that the final display product will be well received.

7. ACKNOWLEDGMENTS

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